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Tool Use, Reuse, and Organization in Command–Driven Interfaces

by

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Abstract

To handle the diverse implements they wield in their workshops, people group tools into functional and task-oriented collections, and set recently-used ones aside for re-use. Surprisingly, these strategies have not been transferred effectively to interactive computer interfaces. The chief problem in designing a command interpreter that lets people reuse and organize their on-line activities is the dearth of knowledge of how users behave when issuing commands to general-purpose computer systems. Consequently, existing user support facilities are *ad hoc* designs that do not really support natural work habits.

Recent studies which examined people's behavior in interactive interfaces paid undue attention to command choice and not enough to complete command lines. By examining both aspects, this thesis abstracts general principles governing how often people repeat their activities from usage data gleaned from different classes of user over several months. These provide design guidelines for "history" mechanisms that make old submissions available for re-use. The problem is to identify likely candidates, and several ways of conditioning the distribution to enhance predictive power are evaluated. A case study of actual usage of a widely-available history system is included.

Users also organize their activities by task and by function. This can be supported by an on-line "workspace" that allows people to group tools for related activities. A system loosely based on the metaphor of a handyman's workbench is described and used to illustrate the problems that are encountered when facilities to expedite interaction are bolted on to existing computer systems.

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Of course there is Judy. Her faith, love and support kept me going through all the slow academic times. My graduate lifestyle was balanced by our many adventures together, where her sheer joy and enthusiasm always shone through. Judy's insistence that I move on from my student role is probably the only reason why this document is finally complete.

Last, but not least, is Adam. No matter how tiring the day was, his ready laughter whenever I returned home always filled me with joy.

Dedication

This thesis is dedicated to my parents, Morris and Bella Greenberg. Due to their religion and the oppressive Eastern European politics of their childhoods, they had no opportunity for advanced education. Yet they never failed to see its importance, and alway encouraged me to pursue its path.

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Chapter 1

Introduction

> There is nothing quite so frustrating for the avid do-it-yourselfer than to begin a project, suddenly need a particular tool, but have no idea where in the house to look for it.
>
> — Practical Homeowner's 1987 Do-It-Yourself Annual,
> Rodale Press, p191

General-purpose computer environments that furnish a large set of diverse tools are often hard to use. Although some difficulty is associated with using any particular tool, this dissertation is concerned with the problems that a person faces when *selecting* a tool from the many available, *reusing* that tool while performing a task, and *organizing* his chosen tools in a way that makes them ready to hand later on. Surprisingly, methods and habits for using physical tools that have evolved over millions of years have not been transferred effectively to the computer domain.

The goal of this dissertation is to identify properties of a human-computer interface that supports how people select, reuse, and organize the tools available in general purpose computing environments. These properties come from empirical analyses of user behaviour. This introduction sets the scene by first reviewing physical tools, from their very natural use by animals to ultra-sophisticated machinery that taxes human capabilities beyond acceptable performance limits. Section 1.2 moves to the focus of this document — general-purpose computing environments that make diverse collections of online tools available. It identifies two problem areas; the dearth of knowledge about people's use of online tools, and the poor existing user support for everyday interactions with them. The final section outlines the major themes covered by each of the following chapters.

1.1 Using physical tools

Until the late eighteenth century, Man distinguished himself from other animals by claiming to be the only tool-user. Since then, ethologists have reported extensive tool use by many species of animals. A few examples follow[1].

The *myrmicine ant* drops debris (bits of leaf and bark) on to soft foods that are otherwise difficult to move. After the food has soaked into the "sponge tool", it is all carried back to the colony (Fellers and Fellers, 1976). The Egyptian vulture feeds on tough-shelled ostrich eggs by picking up a stone in its bill and throwing it down repeatedly until the egg cracks (van Lawick-Goodall and van Lawick, 1968). Figure 1.1 illustrates the well-known woodpecker finch of the Galapagos Islands. Using twigs and cactus spines held in its bill, the finch probes for otherwise unattainable insects living in trees or under bark. The elephant is a frequent tool user too. Twigs and branches grasped in its trunk extend its reach, particularly for scratching and chasing flies away, and the elephant also threatens intruders by waving branches or by throwing missiles at them. Sea otters break open shells by pounding them on rocks balanced on their chests (Hall and Schaller, 1964). Excluding humans, primates are the most habitual tool users of all animals. Depending on the species, untrained monkeys, apes and chimpanzees throw or drop things (stones, branches)

[1]The definitive treatment of tool use by animals is Benjamin Beck's *Animal Tool Behaviour* (Beck, 1980). Unless stated otherwise, all references to tool use by animals and early Man reported in this section are taken from Beck's extensive catalog.

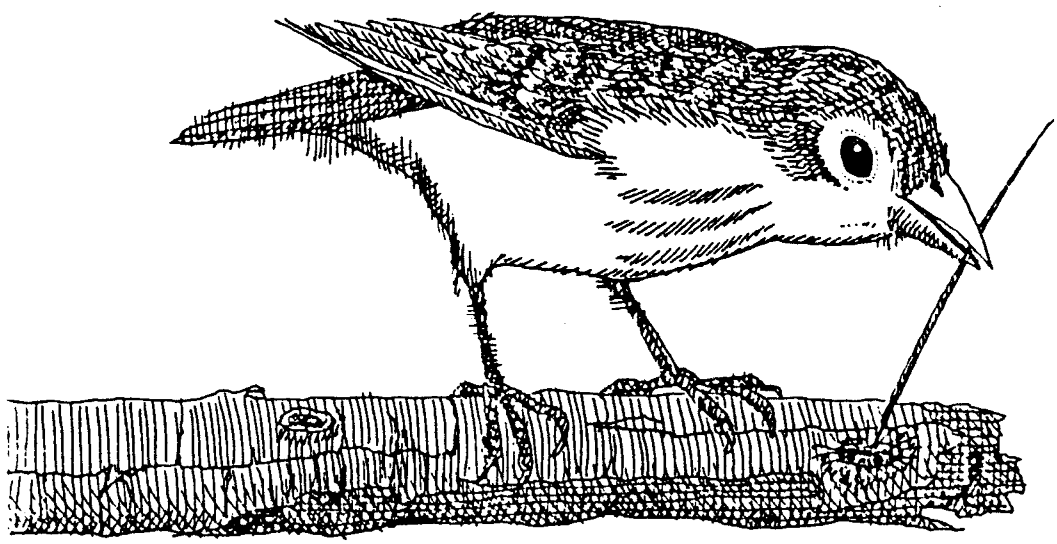

Figure 1.1: The Galapagos finch probing for insects with a cactus spine. Illustration by J. Poehlman, in Smullen (1978) p17

at intruders, use leaves as sponges to gather water, brandish sticks as clubs, wipe wounds with leaves, and use various implements to pound open, extend their reach towards, or probe and rake in food. The extensive tool behaviour of captive chimpanzees is evident to any circus or zoo visitor. They stack and climb upon objects to reach food, and they have been trained to ride bicycles.

Man cannot even claim to be the only manufacturer. Although most animals obtain tools from the natural debris of their environment, a few also fabricate tools. Beck (1980) recognized four modes of tool manufacture in animals. The first is *detach*, as performed by a woodpecker finch breaking off its twig tool from branches. An example of *subtract*, the second mode, is a parrot who removes bark from a twig before scratching himself, or chimpanzees stripping leaves from branches before digging for termites. Some chimpanzees are known to *reshape* pieces of wood into tools with pointed tips by chewing. Finally, implements can be *combined* together, although this has been observed only with captive animals. Chimpanzees, for example, join sticks together to create a further-reaching tool.

Although Man cannot lay claim to exclusive tool use and manufacture, he does distinguish himself by the complexity of his tools, how they are used and reused, and how they inter-relate. First, Man is the only animal known that uses one tool to produce another. This behaviour is believed to date back 2,500,000 years to our hominid ancestors who whittled wooden tools with sharp flakes of stone (Leakey and Lewin, 1978). Second, Man retains tools for repeated reuse, unlike most animals who discard them immediately after use[2]. Again, early hominid records indicate that stone tools were transported from foreign fabrication locations and then used extensively before being discarded. Third, Man uses tools at special-purpose sites. Early hominids had special food preparation areas, while archeological evidence from later periods shows much tool-based activity around the hearth and well-lit work areas (Gowlett, 1984). The final distinguishing point of Man's tool use arises from his tools becoming more numerous and more diverse over the course of history. One only has to step into a modern kitchen or handyman's workshop for proof.

The present age heralds unprecedented availability of numerous tools for individual use. Some, like the hammer, are simple refinements of our ancestor's stone implements. At the other extreme are machines — like airplanes and spacecraft — so complex that only a few highly-trained individuals can use them. During World War II, human ability was pushed to — and beyond — acceptable performance limits by the difficulty of using these complex machines. Some aircraft accidents, for example, were directly attributed to cockpit complexity. This resulted in a demand for experts in psychological engineering — called *Human Factors* in America, and *Ergonomics* in Europe — who recognize human limitations and apply their knowledge to the design of effective human-machine systems (Fitts, 1951). One area of human factors involves designing and simplifying tools that are inherently complex. For example, the highly inter-related controls and gauges in large power plants are

[2] One of the few reported cases of tool retention by animals is the otter, who sometimes keeps shell-cracking stones in his armpit between several successive feeds while diving for other shells (Hall and Schaller, 1964).

often positioned on a map that mimics the physical location of their corresponding devices, making the plant's state easier to understand. Another area of concern — and the theme of this dissertation — is the difficulty of using and managing large collections of loosely-related tools.

When a person's activity is highly dynamic or not readily specified, the actual choice and arrangements of loosely-related tools cannot be effectively predicted by some other person. Instead, people have general methods for structuring their workspaces, and special "organizing tools" for gathering and locating tools and materials. The list below indicates a few important strategies.

Recently used tools are available for reuse. People recognize when a tool just used will be used again in the near future. Rather than select tools and then immediately return them to their original location, they are kept on hand for a period of time. Examples include retaining used cooking implements on counters while preparing a meal, and keeping a dictionary and thesaurus on a desk while writing.

Arranging tools by function. Tools are categorized by function, and each collection is gathered separately. A mechanic, for example, uses the drawers in a tool cabinet to organize wrenches, screwdrivers, ratchets, and sockets. The office worker may arrange her desk with a pen and pencil holder, a stationary drawer, and a forms drawer. A tailor uses pin-cushions, racks for holding spools of thread, shelves for bolts of cloth, and boxes for sewing machine accessories.

Arranging tools by task. People sometimes store together tools that address a particular repetitive task. Workbenches and the tools located on them in a large carpenter's shop may reflect specialized activities; cutting (power saw, blades, fences), preparation (large table, glue, vice, clamps, finishing nails), drilling (drill, bits), nailing (work belt with hammer and nail pouches), and so on.

Figure 1.2: A carpenter's workshop, adapted from page 51 in *Working in Wood*, by E. Scott, Putnam, NY, 1980

The carpenter's workshop in Figure 1.2 illustrates an integrated use of these management strategies. Recently used tools and material lying on the central workbench are readily available for reuse. The tool cabinet and tool panels arrange tools by function, while other work areas are dedicated to certain tasks.

1.2 Soft tools in general-purpose computing environments

1.2.1 Definitions

Some important terms are introduced here. Others are defined and elaborated as needed throughout the dissertation.

A *shell* is the top level interface placed upon a general-purpose computing environment (the characteristics of these environments are discussed further in Section 1.2.2). A shell allows users to access a library of existing programs as utilities, to combine existing utilities as needed, and to extend the library at will. An *activity* or *submission* is defined as a single request submitted to the shell by a person. Activities typically specify actions and arguments. *Actions* are commands that indicate the utility to be invoked. *Arguments* supply information to the utility, through *options* that dictate how it is to work, and *objects* that indicate the computer material to be manipulated. *Incremental interaction* is a style of human-computer dialog characterized by successive activity requests that are submitted to the shell and responded to in turn (Thimbleby, in press). A computer *tool* is another name for a system utility. However, a user may consider the tool as including specific arguments as well.

Interfaces to conventional operating systems provide good examples of incremental interaction dialogs involving all the notions above. One usually submits activities to a top-level command shell by typing simple commands and arguments, although some modern systems augment or replace this primitive dialogue style with menus, forms, natural language, graphics, and so on (Witten and Greenberg, 1985). The user then waits for the utility to do its task before entering the next line.

1.2.2 From appliances to manufacturing

Computers and their uses fall under an enormous variety of often overlapping categories. They range from dedicated turnkey "appliances" that are specialized tools addressing highly specific domains, to interactive programming environments that function as software "manufacturing" plants. This dissertation is only concerned with those general, flexible, and heterogeneous computer environments whose shell provides end users with many diverse tools and materials, selected through incremental interaction. These environments lie somewhere between the extremes above.

The design emphasis in human-computer interfaces for the non-programming mass market is currently on application areas perceived to be used frequently by the target population. There is a proliferation of packages for word processing, painting and drafting, spread-sheet calculations, and so on. These packages may be considered appliances, highly specialized tools handling very specific tasks. Some have excellent interfaces, finely-tuned to meet specific user needs. Modern appliance-oriented top-level interfaces, augmented with a limited repertory of generic capabilities, act as delivery vehicles for these application packages (*eg* the Apple Macintosh; Williams, 1984). However, those users who do not wish to program may only pursue the relatively small set of tasks addressed by the applications which are provided. This poses appreciable difficulties.

> Computers are increasingly used ... in complex areas ... characterized by the lack of generally accepted methods and techniques to be used for

> problem solving. For this reason it is impossible to construct software tools covering problem solving completely.
>
> — Dzida, Hoffmann and Valder, 1987, page 30

At the other end of the spectrum, programming environments provide users with the means to pursue goals not addressed specifically by any one application. Historically, these systems arose from the second and third generation computers that emphasized programming in high-level languages (Denning, 1971). Their contemporary versions are highly interactive programming environments that simplify programming "in the small". Some examples are: SMALLTALK (Goldberg, 1984); INTERLISP-D (Teitelman and Masinter, 1981); PICT (Glinert and Tanimoto, 1984); and PECAN (Reiss, 1984). By analogy, these programming environments are highly sophisticated manufacturing plants that can be re-tooled rapidly to design and create a variety of complex machinery.

While appliance environments are overly restrictive for those wishing to pursue general tasks, programming environments are impractical for non-programmers, for the actions, objects, and complexity of discourse are expressed in programming terms (Cuff, 1980). The computer industry is not blind to this incompatibility, and has spent considerable effort trying to bridge the gap between specialization and generalization through *integrated* systems. This approach groups a set of limited applications into one large integrated product, so that the boundaries between these applications are minimized or eliminated (Nielsen *et al*, 1986). Although a promising direction, these systems currently offer only slightly more power than appliance-oriented computers.

Midway between the two extremes are those top-level interfaces that provide their end users with a rich set of actions and objects, actions ranging from primitive to high-level ones. Each action, together with the object it manipulates, is available as a tool, and they can be combined in simple ways to manufacture new tools, often without resorting to conventional programming. These form the focus of this dissertation. As summarized by Lee, environments in this general-purpose computer genre include

> ...collections of heterogeneous but complementary tools that allow users to perform a wide and varying range of tasks. Furthermore, the environment provides fairly uniform access to the software tools and permits users to use them for various purposes.
>
> — Lee, 1988b

Generally, tools are flexible to use, can be combined in many ways, and are reshaped as needed. In addition, these environments support and encourage both tool manufacture and sharing by a variety of end users.

1.2.3 Problem statement

The hypothesis of this dissertation is that, as with physical tools, people select and often immediately reuse their recently submitted activities to general-purpose computing environments, and consciously organize their activities by both task and function. If this hypothesis holds, then the interface should give the user support by keeping recently-used activities available for reuse and by allowing him to organize activities by function or task.

Yet existing shells invariably either provide uniform access to all system utilities or group them in a pre-defined way. Except for a few *ad hoc* and un-evaluated implementations, there is no on-line support by even contemporary interfaces for people's natural strategies for organizing their workspace. Command-based interfaces, for example, provide uniform access to all system actions, even though actual usage of these commands is far from uniform. "History systems" that allow people to recall old submissions are badly designed, and their effectiveness is unknown.

Menus that explicitly reveal pre-grouped system actions may not reflect the user's actual task organization.

The dissertation addresses two major problems. First, there is a dearth of knowledge of how users actually behave when interacting with a general-purpose environment. Second, current interfaces do not adequately support a user's natural work. Although some have studied how people choose system utilities from a large set, no statistics are available on how people generate, select and repeat their activities. The bulk of this thesis is devoted to filling this void, based upon analyses of long-term observations made of people using UNIX[3], a general purpose computing environment. The experimental findings are then used to derive design principles of a user support facility that aids one's natural work.

1.3 Outline

The dissertation is divided into four distinct parts. Chapters 2 and 3 list how observations of user activity in general-purpose computing environments have been collected and analyzed in the past. The method employed here is described, and selected previous works are replicated and the findings discussed. Chapters 4 through 7 form the heart of the dissertation. They detail how people repeat their activities, and how the results can be applied to designing a facility that lets one reuse (as opposed to re-enter) previous submissions. Chapter 8 examines how people organize activities. Finally, Chapter 9 describes the design and implementation of a user support tool that allows people to both reuse and impose a structure upon their old activities. Each chapter is briefly summarized below.

Chapter 2 introduces a study of natural everyday human usage of the UNIX operating system and its command line interface. The observations made are the

[3]UNIX is a trademark of AT & T Bell Laboratories.

basis for most investigative work performed in later chapters. UNIX is argued to be a general-purpose environment and therefore appropriate for observation. After several existing data collection methodologies are described, the one finally employed is detailed.

Chapter 3 covers previous work on how people use commands in UNIX. The results of several studies are reviewed, and portions of these are replicated. Although the statistical details of the replicated studies are supported, some of the conclusions made by the original researchers are misleading. In particular, studying command use — the verbs of a command line — is not sufficient and presents a distorted view of what is actually occurring. The complete command line entered by the user must be considered too.

Chapter 4 introduces and surveys existing reuse facilities that let users recall, modify, and re-submit their previous entries to computers. Although the survey is not exhaustive, it is representative of facilities on commercial, state of the art, and research systems. The chapter concludes by noting that there is no empirical evidence justifying any of these designs, either *a priori* through knowledge of how people repeat activities, or *post hoc* through evaluating their actual use.

Chapter 5 continues by providing empirical evidence that people not only repeat their activities, but that they do so in quite regular ways. It starts with the notion of *recurrent systems*, where most users predominantly repeat their previous activities. A few suspected recurrent systems from both non-computer and computer domains are examined in this context to help pinpoint salient features. The UNIX data is analysed from this perspective, particular attention being paid to the statistics of complete command line recurrences. Although people are seen to generate many new activities, old ones are repeated to a surprising degree. The probability distribution of the next submission repeating a previous one as a function of recency is also reported.

Chapter 6 considers the potential and actual reuse opportunities within UNIX.

First, several methods are suggested that could increase the likelihood that the next submission occurs in a small set of predictions offered to the user for review and reuse. The UNIX data is conditioned by these methods, and the resulting improvements are determined quantitatively. The second part of the chapter investigates how well the reuse facilities supplied by the UNIX shell are used in practice.

Chapter 7 summarizes the results as a set of design principles, and existing reuse facilities are revisited and briefly criticized from this perspective. The findings of previous chapters are then corroborated by analyzing a different domain — a functional programming environment — as a recurrent system. A final discussion concludes that the notion of reuse facilities are conceptually, as well as empirically, justified as a user support tool.

Chapter 8 argues that a user organizes his computer activities by task and by function. The concept of a user support tool called a *workspace* is developed. Similar to a physical workspace, this online facility allows people to reuse and organize their tools for their related activities. Although the idea is not new, several novel properties of workspaces are elaborated. This chapter reveals how limited our knowledge is in this area and suggests that much more investigative research is required — work that is beyond the scope of this dissertation.

Chapter 9 describes the design of a system that loosely follows the metaphor of a handyman's workbench. It embodies the reuse properties suggested in Chapters 4 through 7, and the structuring properties of Chapter 8. The implementation is a front end to UNIX, and serves to illustrate that serious pragmatic problems are encountered when user support tools are built as add-ons to existing systems. The problems encountered during its design and use indicate a few open research areas.

The thesis ends with a brief concluding chapter. The contributions are summarized, and future research directions are proposed.

Chapter 2

Studying Unix

This chapter introduces a study of natural everyday human usage of the UNIX operating system and its command-line interface. Analysis of the data collected is central to the pursuit of knowledge of user behaviour when interacting with general purpose environments. The chapter begins by describing UNIX and gives reasons why it is an appropriate vehicle for research. Section 2.2 reviews several methods of data collection used with previous UNIX investigations, while Section 2.3 describes the details of the current study. Analyses of data is deferred to later chapters.

2.1 Choosing Unix

Why perform natural studies on UNIX, with its baroque and outdated user interface, instead of controlled experiments on a modern system? This section starts by advocating a natural study for exploratory investigation of human-computer interaction. After recognizing several pragmatic problems with such investigations, UNIX is introduced and its choice is justified.

2.1.1 Natural studies

The thrust of this thesis is that it is possible to capitalize on patterns evident in human-computer interaction by building special user support tools. A prerequisite is to first "know the user" (W. Hansen, 1971). One way is through analysing everyday natural user interactions with current systems so that existing patterns of activity can be discovered and exploited. S. Hanson *et al* justify this approach by contrast with traditional controlled experimentation.

> Although [a controlled experiment is] appropriate and useful in theory-guided research ... it is less appropriate when the researcher needs to identify new variables or complex unknown relations between new variables. Nor does it deal efficiently with highly multivariate phenomena such as human-computer interaction. Where neither theory nor time will tolerate the isolation of a few controlling variables, assessing people's natural use of a computer system may be highly informative. ... Generally, observational data of human-computer interaction can allow the testing of simple hypotheses and intuitions, the discovery of computer features that cause problems for users, and guidelines for interface design.
>
> — Hanson, Kraut, and Farber, 1984

Investigating people's natural behaviour when using computer systems is not easy. Several major problems present themselves. First, there is no established methodology of study. Past experimenters used various different methods, leading not only to hard choices for new researchers, but also to difficulties for those wishing to contrast or replicate results of previous work. Even when similar methods are chosen, the lack of controls make comparison questionable. Investigations are often performed on widely different or rapidly evolving operating systems and user interfaces, and habits of user populations may be site-specific.

A second problem with natural studies of user interfaces is the difficulty of collecting data. Monitoring real-life human-computer interaction is not easy. Source code may not be available for modification; interactions may go through a suite of programs rather than through a single one; security measures at the site may preclude close study. Furthermore, subjects may be hard to obtain. People resist conscription, perhaps due to concerns about privacy or plain inertia, or site populations are just too small for adequate sampling. Corporate reluctance also hinders data collection, for computer and human resources are expensive. Monitoring users takes processor time, physical records of user activities need substantial disk space, and subjects' time is costly.

With these provisos in mind, natural studies can, at least in principle, give valuable insight into people's behaviour when using computers. One popular vehicle for such studies is UNIX.

2.1.2 A brief introduction to Unix

UNIX is a widely-used multi-tasking operating system that runs on a variety of different computers, and is well described in many academic and popular publications (*eg* Ritchie and Thompson, 1974; Kernighan and Mashey, 1981; Pike and Kernighan, 1984; Waite, 1987). From the user's point of view, it has a variety of important components. One is the file system, where all files are organized within hierarchical directories. Directories and files can be manipulated by users in all the standard ways. Users often work within the confines of a single "current" directory, although resources located in other directories are generally available as well.

Another important feature of UNIX is that no distinction is made between files containing programs and those containing other things; any file is eligible for execution[1]. Although UNIX contains a large but standard repertory of programs,

[1] Technically, an execution bit has to be set before a file can be run as a program. However, this

there is no difference between invoking a system program and a user program. This is significant because it allows one to tailor a system to individual needs simply by writing utility programs and putting them in the right place, without having to alter the innards of the system in any way. By setting search paths, users can tell UNIX to look for executable programs in specific directories containing the standard system libraries, one's own personal libraries, or files belonging to other members of the community. However, this flexibility has drawbacks. It encourages users to build and share extensive libraries of commands, causing difficulty with the naming of different programs and multiple versions of programs. Others may have come to rely on programs in a personal library without the owner's knowledge, in the erroneous belief that they were "standard" utilities (Witten and Greenberg, 1985).

The third UNIX component is its user interface, a command line interpreter called a *shell*[2] that comes in several flavours, the most popular in America being *csh* (Joy, 1980). As with most conventional command-driven systems, *csh* is a passive slave awaiting orders; no attempt is made to guide or help the user. *Csh* implements incremental interaction. Once an order is received, it carries it out and then awaits the next command. Despite the proliferation of screen-based programs (especially editors), the basic *csh* interface is teletype-like. No use is made of the cursor control features provided by most VDU's. With the exceptions of the character-erase, word-erase, and line-erase capabilities, the screen is treated as a long roll of paper. Through the shell, users compose, edit, and then submit an input line to UNIX. The usual form of a submission is a command, optionally followed by an argument list[3]. Although the command may be handled directly by *csh*, it typically creates a new process by executing a file containing either compiled code produced by a programming language, or a script of further command lines. The argument list

---

bit can be easily set by a user with the appropriate permissions.

[2]The command line interpreter is called a *shell* because it surrounds the kernel of the operating system (Quarterman, Silberschatz and Peterson, 1985).

[3]Although *csh* contains a rudimentary programming language, it is rarely used at the command line level.

is made available to the program, and it can have two components: options and objects. Options modify the standard meaning of the program *ie* they "reshape" the tool. The program acts on the objects, which are usually UNIX filenames or strings. Arguments may contain regular expressions that are replaced by the shell with the names of files matching the expression.

UNIX users can tie together resources by redirecting input and output between programs, files, the keyboard and the screen; this feature distinguishes UNIX from other command line systems. A standard UNIX program takes its input from the keyboard and places its output on the screen. Yet the same program can work with files, simply by using the two redirection symbols '<' and '>', which stream input from file to program and output from program to file respectively. Program-to-program communication is supported through the pipe symbol '|', eliminating the need for explicit temporary files. For example, consider the *sort* command that sorts its input lines, and the *uniq* command that removes succeeding copies of identical lines. Typed by itself, *sort* waits for a user to enter all the input lines through the keyboard, and prints the ordered results to the screen afterwards. In the command line *sort* < *in* > *out*, the lines in the file *in* are sorted and then written to the new file *out*. Finally, the sequence *sort* < *in* | *uniq* uses the output of *sort* as the input to *uniq*; an ordered list of the unique lines contained in the file *in* are written to the screen. Through redirection and pipes, the user can "combine" his UNIX tools.

Because no distinction is made between user and system software, and because input and output are easily passed between programs, UNIX works well when many small, general-purpose modules are available as building blocks for new programs. This follows from the cornerstone philosophy of UNIX:

> Make each program do one thing well. To do a new job, build afresh rather than complicate old programs by adding "new" features. Expect the output of every program to become the input of another, as yet

unknown program. ...Do not insist on interactive input[4].

— McIlroy, Pinson and Tague, 1978

The building blocks approach has drawbacks. Although small programs can be combined in many ways not anticipated by the original designer, it is sometimes hard to perform common operations without resorting to some level of rudimentary "programming". Less experienced users are often overwhelmed by the complexity of the system (Dzida, Hoffmann and Valder, 1987). Still, it is the power and richness of UNIX that makes it interesting. Because diverse utilities are available, and program creation and sharing are encouraged, UNIX fits the description of a general-purpose environment given in the last chapter.

2.1.3 Why study Unix?

UNIX is a twenty-year old operating system whose command line interface no longer represents current ideas in interface design[5]. Even at its best, the UNIX interface is full of well-known deficiencies (Norman, 1981). Then why study UNIX? Why not look at, say, a modern icon-based interface instead? This section argues that studying UNIX is indeed fruitful for several reasons: it generalizes across many other systems; a body of knowledge of UNIX behaviour currently exists; and finding and monitoring subjects is relatively straightforward.

Generalization. One attraction of UNIX is that it is not a contrived "toy" system. Rather, it is widely used, very powerful and potentially complex, and has a

[4]Some people believe that current versions of UNIX have seriously compromised the "one tool one job" philosophy (Pike and Kernighan, 1984; Wait, 1987).

[5]UNIX was first developed in 1969 by Ken Thompson and the Computer Science Research Center of Bell Laboratories in Murray Hill. Originally written for the DEC PDP-7 computer and influenced by the Multics operating system, it was not publically licensed and widely released until 1976 (Quarterman *et al* 1985).

broad range of users (Kraut, Hanson and Farber, 1983). Because it is a general-purpose computing environment fulfilling many needs, any results garnered from it may generalize to other systems. In contrast, many high-performance graphical interfaces are so customized to particular applications that generalizations would be difficult to make and support.

Although direct-manipulation systems are becoming more popular, command line interfaces like UNIX still pervade computer use. Some examples from mainframe and personal computing environments are Vax VMS, Honeywell Multics, Apollo Domain, CPM, and IBM VM and DOS. Hierarchical menus based on either text or graphics are usually little more than syntactic sugar placed on top of a command line system[6]. Observations made of UNIX usage probably apply to all these systems too.

If UNIX findings could not be generalized, they would still be valuable in their own right. Although old, UNIX is far from dying. Rather, it is being rapidly disseminated as a *de facto* open system standard on diverse machines, running the gamut from mainframes to workstations and personal computers. Even users of graphical direct-manipulation interfaces thirst for UNIX, as illustrated by Apple's Macintosh/UNIX fusion. Vendors are now trying to modernize UNIX by embedding it within a window environment. The Sun workstation, for example, has a suite of window-based front ends to popular UNIX facilities, including the shell, debugger, mail system, terminal emulator, and so on (Sun Microsystems, 1986a).

An existing body of knowledge. Another appeal of UNIX to researchers is that it has already been studied extensively. There is probably more knowledge and raw data on UNIX usage than any other computer system. The scientific process is more easily realized; other UNIX studies can be replicated, and previous findings can be

[6]MENUNIX, summarized in Chapter 8, is an example of a menu-based interface built directly on UNIX (Perlman, 1984).

built upon.

Finding and monitoring subjects. A pragmatic advantage of studying UNIX is that it is relatively easy to do, since large groups of diverse people use it at many different sites. Although generally perceived to be expert-oriented, there is no question that a significant number of non-programmers with widely varying needs also harness its powers. UNIX is often the standard system employed by research institutions. The benevolent setting allows large-scale realistic studies that span user categories.

At the University of Calgary, for example, UNIX is used heavily in the Department of Computer Science by people with quite diverse programming skills and personal requirements. It is also available to people in several non-computer departments. The academic setting not only provides a captive audience, but also encourages participation — bureaucratic procedures are in place for conscripting subjects for study. Finally, UNIX source code for its programs are available for modification.

In summary, it is assumed that observed usage patterns of UNIX are fundamental to most computer-based imperative interactions. Methodological motivation arises from the number of diverse users, the relative ease of collecting data, and the existence of other findings for comparison. Studies of UNIX usage are generalizable, and have already affected the design of leading-edge systems. For example, Card and Henderson (1987) describe a multiple virtual-workspace interface to support user task switching, motivated by the UNIX study of Bannon, Cypher, Greenspan and Monty (1983) (see Sections 8.3 and 8.1).

2.2 Techniques for analysing activities of Unix users

As mentioned previously, a problem with many computer studies is the lack of a standard methodology for data collection. UNIX is no exception, and records of interactions obtained range from low-level input traces collected over large user populations through to protocol analysis elicited from a few select subjects. This section surveys common methods that have been used for studying UNIX, and indicates their associated drawbacks.

2.2.1 Traces of user activity

A record of interactions between user and computer, usually collected through an unobtrusive software monitor, is called a *trace*. In natural studies of UNIX usage, voluminous amounts of data are often collected and sifted through in the hope that something interesting may turn up. Alternatively, a subject may be asked to solve particular problems, and his performance monitored over short-term tasks. This second approach is fruitful for testing hypotheses about user behaviour and for exploring sub-domains of UNIX. A measure of validity is obtained by comparing traces generated by the artificial task to those generated under normal circumstances (Lewis, 1986).

The methods listed below describe ways that traces have been generated on UNIX.

Method 1: Recording all keystrokes entered. Every single character entered on the command line is recorded, including the special line-editing characters (*eg* <backspace>) and non-alphanumeric characters (*eg* <return>). The monitoring software is fairly easy to write. In UNIX, for example, an interposed pseudo-tty filter can catch and note all keystrokes on entry before passing them on to the primary application. This easily-implemented method supplies a complete record of all input. Yet there are several disadvantages. First, unnecessary data is collected. Unless the study is concerned with line editing or similar low-level concerns, no benefit is gained by including such primitive operations. The final line, as seen by the user before a <return> is selected, would suffice for most purposes. Second, such traces are not easily read due to the inclusion of special editing characters. Consider, for example, the following input characters for a line taken from a typical script (Lewis, 1986), where $\wedge H$ represents a <backspace>, $\wedge M$ a return, and $\sqcup$ a space:

$$lsa \sqcup \wedge H \sqcup \wedge H \wedge H \sqcup \wedge H \wedge H \sqcup \wedge Hm - \wedge H \sqcup \wedge H \wedge H \sqcup \wedge Hs \sqcup -F \wedge M$$

After editing, the line translates to *ls -F*[7]. A third more serious disadvantage is that the *csh* manipulations of the line are not recorded. Once a line is entered, the *csh* expands wild cards, history substitutions and aliases. Although the expanded line may reflect the intention of the user more closely, it is not captured by recording keystrokes only.

Method 2: Session Transcripts. A variant of recording keystrokes is recording complete transcripts of a login session, which includes the user's input and the system's response. Saving transcripts as human-readable textual records is simple when the user interface follows a glass-teletype style of dialog. When cursor control or graphical interaction is used, the transcript may be viewed as an animated playback record instead. Transcripts are information-rich, which is their weakness as well as their strength. Although they work well for small studies involving short

[7] The number of keystrokes used to enter text is significantly more than the number of final characters. In a study of document creation through an editor, Whiteside *et al* (1982) observed that only one-half of a user's keystrokes are for text entry. The rest were for cursor movement (1/4), text deletion (1/8), and so on.

sessions, the data produced for anything larger is so voluminous that it is almost impossible to handle. Transcripts are best used in pilot studies, or as a way of augmenting other data collection methods.

For example, Akin *et al* (1987) performed a case study of the structure of the UNIX directory space by reviewing transcripts of users asked to carry out certain tasks. Even though only two subjects were used, and the task duration was limited to half an hour, they reported that the records were lengthy and hard to analyze. However, the transcripts did provide insight into user's movement in the directory space.

Method 3: Recording lines expanded by csh. Instead of collecting data by catching keystrokes as they are entered, the complete line submitted can be captured as a chunk after it has been entered and processed by *csh.* All the noise produced by line editing would be removed. This is easily accomplished through the *csh* history facility, where lines automatically recorded by the system can be saved in a file. Desmarais and Pavel (1987), for example, collected and analyzed short-term UNIX traces by this method, and applied the information to generation of user models.

Extra information known to *csh* can be trapped and noted as well by placing "hooks" within *csh.* Inline expansion of history use, aliases and regular expressions could be included, as well as the current working directory of the user and the error status after execution is attempted. This is the method used in the current study, and will be described further in Section 2.3.

There are several problems with recording lines from within *csh.* First, the source for *csh* must be modified if extra information is desired. Since this contains over 16000 lines of sparsely documented and quite complex code, the task is daunting[8]. Second, and more seriously, not all user activity is captured. Although recording *csh* lines works well for "batch" style programs that execute and return without user intervention, it is not appropriate when highly interactive applications are used (*eg* editors). Interactive information is lost since data is collected from the *csh* command line only. Also, commands cannot be considered "equal." For example, consider a trace containing only two UNIX commands: *ls* for listing files; and *emacs* which invokes a sophisticated interactive editor. Whereas file listing is accomplished almost immediately, an editing session can last for hours. This distinction is not captured by *csh*. A further disadvantage with this recording method is that the actual processes spawned by the command line are not noted. There are many ways to execute programs in UNIX; directly by name, indirectly through an alias or *csh* variable, or as a suite of programs through a script. Because of this diversity, users can invoke the same program by many different names. For example, *e*, *emacs* and *ed* may all invoke the same editor. As only the text typed to *csh* is collected, the actual processes executed is left as an educated guess.

Tracing lines expanded by *csh* is a tradeoff between recording too much and too little information. By selectively combining this method with other ways of recording data, most problems noted above are correctable. For example, Lewis (1986) includes the final expanded line along with the command line as issued.

Method 4: Recording processes spawned by user's commands. A popular method of analyzing UNIX usage exploits data collected by the standard system accounting packages, which records the processes spawned from a user's command rather than the command itself. The advantages lie in the ease of collecting data, and in having a record of the system's response to the user's activity. Unlike some previous methods, no program generation or modification is necessary.

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[8]Four months were required to produce an acceptable tested version of *csh* that included a robust monitoring facility, even though the final number of modifications required was relatively small. This time includes the bureaucratic red tape involved with obtaining *csh* source.

But recording processes spawned is severely limited. First, many commands spawn multiple processes not mentioned explicitly by the user. Recording of processes only reflects the user's command selection when the generated process matches the submitted command, which is often not the case. A command may create multiple processes, and inferring what was actually typed by the user can be difficult. Researchers using this method have to develop strategies for eliminating the extra processes from the record. These include sifting the data by hand (Bannon and O'Malley, 1984), by a filter (Draper, 1984), or by supplementing the process data with command-line data (Kraut *et al*, 1983).

Another major problem with recording processes only is the impoverished information produced. All options and arguments qualifying the command are lost, since the record only indicates the processes executed. Yet these are critical for understanding how a command is used. Also, commands handled directly by *csh* cannot be detected, as they do not spawn new processes (*eg* Draper, 1984). Further, the use of aliases and history use is not noticed, since processes are created only after the line has been expanded.

A final problem stems from the difficulty of handling processes generated from user-written programs or scripts that are not part of the standard UNIX library. These are surely important, for UNIX encourages users to supplement system software with personal software. Yet some previous studies simply ignored those processes that were not within the system domain, usually by filtering out the unknown ones from the process list (Draper, 1984). Still, noting processes gives a reasonable approximation of the commands entered and executed by users.

2.2.2 Protocol analysis

Although some analysis of user activities is possible by studying traces, inferring a user's high-level intentions from a low-level record is always difficult. A better method of discovering intentions is to have users describe their activities as they are performed, a technique called *protocol analysis*. Some ways that protocol analysis has been used within UNIX are noted below.

Method 5: Annotation of traces. Users are asked to annotate periodically a history list of commands with their intentions during a login session, perhaps by thinking aloud or by textual inline comments. For example, Jorgensen (1987) instructed subjects to talk aloud while performing an artificial task involving UNIX mail. Their comments were recorded on audio tape and the important ones were later merged with transcript logs collected by the second method. Similarly, talking aloud into a tape recorder has been used for UNIX studies by Jennifer Jerrams-Smith[9].

The example below gives a portion of a textually annotated trace, as recorded by Bannon *et al* (1983).

< *Write Info Retrieval report. Its going to take a long time and be interrupted by other activities*>
15 vi IRreport
< *Interrupted to prepare a memo. Send note to gm about outcome*>
16 snd gm
<*back to IRreport*>
17 fg
18 lf HMI ...

Alternatively, the researcher may take a more active role and discuss the trace with the user either during or after the session (see method 7).

An objection to this form of protocol analysis is its obtrusiveness. Because of this, annotations are sometimes deferred until the end of an interactive session. Perhaps more serious is that annotations may not reflect actual intentions. When

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[9] J.Jerrams-Smith, AI Group, Philips Research Laboratories, Redhill Surrey, UK.

comments are noted after a set of activities are performed, they may reflect *post hoc* rationalizations of actions rather than real situations (Suchman, 1985).

Method 6: Constructive interaction. One way of removing the disruptive effect of annotations is through *constructive interaction*, where natural discussion between interacting participants of a study are used to reveal underlying processes (Miyake, 1982). When applied to studies of human/computer interaction, cooperating users are videotaped solving a problem on a computer, although other resources may be made available to facilitate discussion. This is a good way of revealing the users' mental model of particular concepts, especially when one or both participants are discussing a topic they do not fully understand (O'Malley, Draper and Riley, 1984; Suchman, 1985).

In contrast to regular thinking aloud (fifth method), Jorgensen (1987) noted that sessions involving constructive interaction were "more lively, and that far more points were elicited spontaneously." He also suggested that subjects were encouraged to continue their tasks by the presence of their colleagues. On the down side, he reported that the mixing of two individual lines of thought into one sometimes produced a confusing picture of events.

Method 7: Interviews and questionnaires. A simple method of eliciting knowledge about the high-level intentions of a user is through questions asked before or after he performs his task[10]. A group of users may be queried on paper (questionnaires) or verbally (interviews) for their views on the system. For example, Sutcliffe and Old (1987) used a questionnaire to elicit preliminary information on user experiences, attitudes and knowledge with UNIX, and the typical tasks performed. Command traces were then logged through the fourth method above.

[10]Since they are not performed during the task, interviews and questionnaires are not, strictly speaking, methods of protocol analysis.

Name	Sample size	Total number of command lines	Number of command lines excluding errors		
			total	mean	std dev
Novice Programmers	55	77423	73288	1333	819.8
Experienced Programmers	36	74906	70234	1950	1276.0
Computer Scientists	52	125691	119557	2299	2022.9
Non-Programmers	25	25608	24657	986	1155.6
Total	168	303628	287736	1712	1498.8

Table 2.1: Sample group sizes and statistics of the command lines recorded

These were annotated in a set of follow-up interviews where users were asked to verbalise their recorded task sequences. Sutcliffe and Old mention that system logs proved the most valuable of the three methods.

2.3 Data collection for the current study

In this study, command-line data was collected from users of the UNIX *csh* command interpreter The selection and grouping of subjects, and the method of data collection, are described below.

Subjects. The subjects were 168 unpaid volunteers. All were either students or employees of the University of Calgary.

Subject use. Four target groups were identified, representing a total of 168 male and female users with a wide cross-section of computer experience and needs. Salient features of each group are described below, while the sample sizes (the number of people observed) are indicated in Table 2.1.

Novice Programmers. Conscripted from an introductory Pascal course, these had little or no previous exposure to programming, operating systems, or UNIX-like command-based interfaces. Such subjects spent most of their computer time learning how to program and use the basic system facilities.

Experienced Programmers. Members were senior Computer Science undergraduates, expected to have a fair knowledge of programming languages and the UNIX environment. As well as coding, word processing, and employing more advanced UNIX facilities to fulfill course requirements, such subjects also used the system for social and exploratory purposes.

Computer Scientists. This group, comprised of faculty, graduates and researchers from the Department of Computer Science, had varying experience with UNIX, although all were experts with computers in general. Tasks performed were less predictable and more varied than other groups, spanning advanced program development, research investigations, social communication, maintaining databases, word-processing, satisfying personal requirements, and so on.

Non-programmers. Word-processing and document preparation was the dominant activity of this group, made up of office staff and members of the Faculty of Environmental Design. Little program development occurred — tasks were usually performed with existing application packages. Knowledge of UNIX was the minimum necessary to get the job done.

Since users were assigned to subject groups only through their membership in identifiable user groups (*eg* Computer Science graduate students), their placement in the categories above cannot be considered strictly rigorous. Although it is assumed that they generally follow their group stereotype, uniform behaviour is not expected.

Instructions to subjects. As part of the solicitation process, subjects were informed verbally or by letter that:

- data on their normal UNIX use would be monitored and collected at the command line level only;
- the data collected would be kept confidential;
- any public reference or dissemination of the data and derived results would guarantee anonymity, unless explicit permission was given by the subject to do otherwise;
- at any time during the study period the subject could request that data collection stop immediately;
- there would be no noticeable degrading of system performance;
- if requested, data collected from a subject would be made available to him or her.

Appendix A includes a typical information sheet provided to subjects. Subjects did not require nor did they receive any additional instructions during the actual study period. No subject asked to be withdrawn from the experiment, and no-one asked to see their personal data.

Apparatus. A modified *csh* was installed on three VAX 11/780's located in the Department of Computer Science and one VAX 11/750 in the Faculty of Environmental Design, both within the University of Calgary. Many different terminals were available to participants, most which were traditional character-based VDU's. In addition, Corvus Concept workstations running the Jade Window Manager were available to members of the Experienced and Computer Scientist groups (Greenberg *et al*, 1986). This workstation allowed users to create many "virtual terminal" windows, each running *csh*, on a single screen.

Method. Command-line data was collected continuously for the four months between February 1987 through June 1987 from users of a modified Berkeley 4.2 UNIX *csh* command interpreter (Joy, 1980). From the user's point of view, monitoring

Code	Description	Example
	Login session record	
S	Start time of the login session	S Fri Feb 6 15:54:25 1987
E	End time of the login session	E Fri Feb 6 17:25:01 1987
	Command line record	
C	The line entered by the user	C ls –a
D	The current working directory	D /user/greenberg/bin
A	The alias expansion of the previous command (if any)	A ls –a
H	The line entered had a history expansion in it (True or Nil)	H True
X	The error detected in the line by *csh*(if any). A following letter and number code indicates the category and actual error type.	X N 10

Table 2.2: Trace information annotated by the modified *csh*

was unobtrusive — the modified command interpreter was identical in all visible respects to the standard version. The total number of command lines recorded per group are listed in Table 2.1.

Data was collected by the third method of Section 2.2.1 — recording lines expanded by *csh*. Table 2.2 lists the trace information annotated by the modified *csh*. Login sessions are distinguished by a record that notes the start and end time of each session (the 'S' and 'E' fields in the Table). Command lines entered during this period are then listed in following records, each annotated with the current working directory, alias substitution (if any), history use and error status. The final command line accepted by *csh*, including history expansions and ignoring editing operations that form the line, is recorded in the 'C' field. The 'D' field notes the directory the user was in when the command line was entered. The alias expansion of the line is found in the 'A' field, while the 'H' field indicates whether or not *csh* history helped form the line. System errors generated by *csh* are registered in the 'X' field. Although eleven categories and many sub-categories of errors are annotated, the distinctions between them are not used in the current study. The total and average number of command lines collected excluding these errors are listed in Table 2.1

An example trace is given in Appendix B. Appendix C provides summary statistics for each subject, which includes the number of login sessions, the command lines entered, the different commands used, the *csh* errors noted, the times history was used, and the different directories accessed.

Data Selection. If subjects did not log in at least ten times and execute at least 100 commands during the study period, their data was not considered. By these criteria, 12 of the 180 original participants were rejected. Particular manipulations of the data, the analyses performed, and the results obtained are described in later chapters.

Motivation. Participants used UNIX as usual. Users were neither encouraged nor expected to alter their everyday use of the system. As subjects had few reminders that their command-line interactions were being traced, they were largely oblivious to the monitoring process.

Availability of data. All data collected is available to — and has been used by — other researchers. A research report describes its format, and includes a cartridge tape of the data (Greenberg, 1988). The report and data is available from either the Department of Computer Science, University of Calgary, or from the author. To ensure the confidentiality promised above, data was massaged to remove the identity of subjects.

Problems. Due to implementation difficulties, the details of history directives are not recorded. The altered *csh* indicates only that history has been used, and notes the command line retrieved through history. It does not record the actual history directive used to produce the modification.

Concluding remarks

This chapter argued that it is worthwhile to study data collected from everyday use of UNIX. Previous methodologies used for capturing UNIX interactions were examined, and the particulars of the method employed by the current investigation were listed.

One difficulty of studying and analysing UNIX comes not from considerations of methodology, but from personal biases of the scientific and user community. Because UNIX is so popular, and because reports of its deficiencies (and corresponding remedies) are so numerous, it is perceived by some to be a "straw man" that is easily picked upon. A reaction to yet another UNIX study could be apathy. Yet all UNIX investigations are not alike. The main purpose of this study, like a handful of others, is not to improve UNIX — it is too late for that. Rather, I assume that UNIX investigations are best harnessed to illuminate fundamental properties of human behaviour when using similar general purpose environments. If doubts exists about generalization, the methodology may be applied to other systems for empirical comparisons.

This study could have been performed on almost any other system with a rich set of constructs. UNIX *csh* was chosen for pragmatic considerations, and because I believe its usage reflects that of other systems.

Chapter 3

Using Commands in Unix

This chapter examines how people use commands in command-based systems[1]. Like previous work, it is based on an analysis of long-term records of user-computer interaction with the UNIX *csh* command interpreter, collected as described in the previous chapter. The results of the major studies are re-evaluated, particularly those of Hanson *et al* (1984) and Draper (1984), and some of the work is replicated. Although the statistical results of the studies are supported, some of the conclusions made by the original researchers are misleading.

The sections provide details of how people direct command-based systems in terms of how individual commands are selected and the dependencies between these commands. It is essential to take into account the fact that pooled statistics may conceal important differences between individuals. As a consequence, the results are analyzed by user and by identifying groups of similar users, as well as by pooling data for the entire population.

For the current study, a *command* is the first word found in the command line entered. Those lines that produced system errors were not considered. The

[1]Some of the findings in this chapter were first presented at the 3rd IFAC Conference on Man-Machine Systems, Oulu, Finland (Greenberg and Witten, 1988b).

first word is parsed by removing all white space at the beginning of the line and counting all characters up to but not including the next white space or end of line. The parsed word is almost always a true UNIX command or alias that invokes a program or shell script. This method does not record all the UNIX commands used, for an input line may contain more than one command (*eg* by redirecting input and output with pipes, or by cascading separate command sequences). Still, it seems a reasonable approximation.

3.1 Frequency distributions of commands for large groups

Several investigators have examined the frequency of command usage by a user population (Peachey *et al*, 1982; Kraut *et al*, 1983; Hanson *et al*, 1984; Ellis and Hitchcock, 1986). All studies report results approximated by a Zipf distribution, which has the property that a relatively small number of items have high usage frequencies, and a very large number of items have low usage frequencies (Zipf, 1949; Witten *et al*, 1984).

A looser characteristic of this kind of rank distribution is the well-known 80-20 rule of thumb that has been commonly observed in commercial transaction systems — 20% of the items in question are used 80% of the time (Knuth, 1973; Peachey *et al*, 1982)[2]. In measurements recorded from a UNIX site, Hanson *et al* (1984) report a similar trend — 10% of the 400–500 commands available account for 90% of the usage. These models also hold for the frequency distribution of all help requests made for particular commands through the UNIX on-line manual[3] → §5.3.1 (Greenberg, 1984).

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[2]This rule is recursive, as the 80 – 20 also applies to the most active 20% (Knuth, 1973).

[3]Every command in the UNIX system has a corresponding manual entry, invoked by typing *man <command>*.

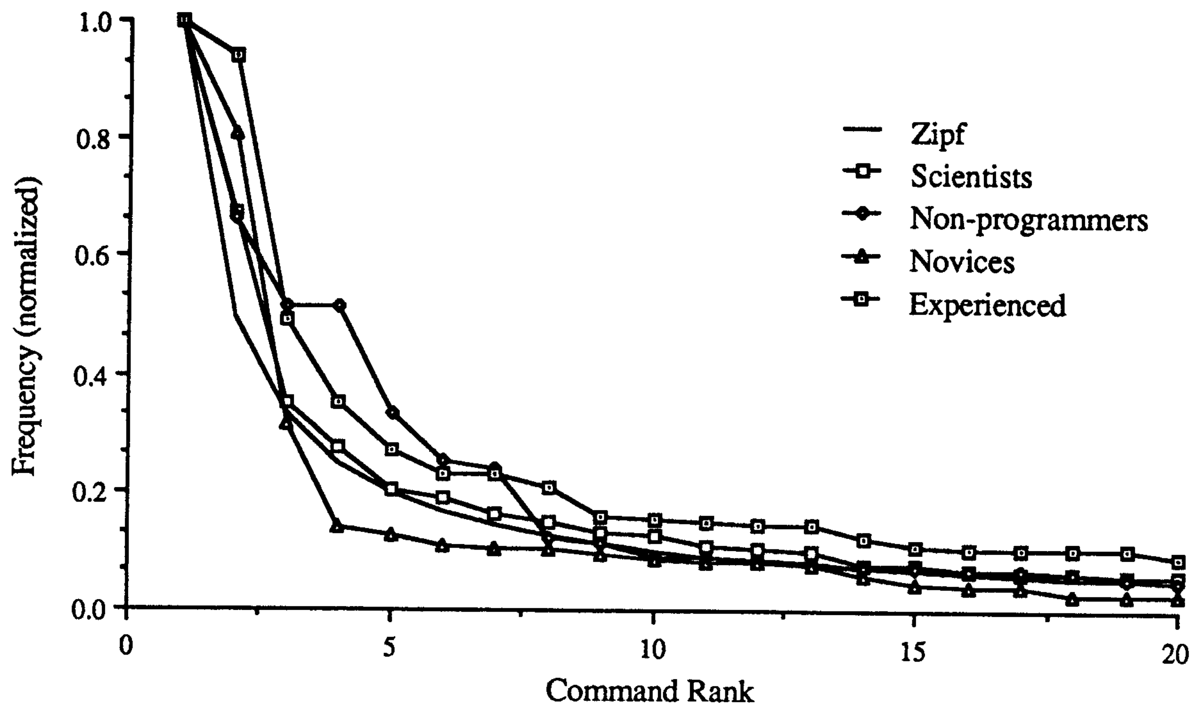


Figure 3.1: The normalized command frequency, compared with Zipf

The current study supports these observations. Figure 3.1 illustrates the command frequency distribution for each of the four different user groups described in the previous chapter. The frequency distribution is not a probability distribution. It gives the relative frequency between commands, rather than the actual frequency of use. The vertical axis shows the number of command invocations, normalized to one for the most frequent, while the horizontal axis shows the rank ordering of commands, with the most frequent first. Only the twenty highest ranking commands for each group are shown. For example, the most frequently selected command by the experienced programmer group is positioned first in the rank order, and is used at a relative frequency of 1. The second most selected (rank order of two) is used at a relative frequency of 0.94, the third at 0.49, the fourth at 0.35, and so on down the list. The Zipf curve, normalized in the same way and calculated as $y = x^{-1}$, is illustrated by the smooth line in the Figure, and seems to provide a plausible model for the observed frequencies. For each of the four user groups, 10% of the commands used accounted for 84–91% of all usage (*cf* Hanson's 10%/90%)[4]. This ratio seems independent of both the actual number of different commands used by a group and the size of the sample group.

3.2 Usage frequency of particular commands between groups

Even though frequency statistics of different groups are modeled by the Zipf distribution, it is worth asking whether commands retain their same rank order between different user groups. If they do, then a command used frequently by one group will have the same relative usage in another. As will be seen, this is not necessarily the case.

Table 3.1 gives the data from which Figure 3.1 is drawn. Each column shows the 20 most frequently used commands by each group (including data reported by Hanson *et al*, 1980) and also gives the total number of commands executed, the number of different commands executed, and the number of users sampled. The few common high-frequency commands across the five user groups are mostly concerned with navigating, manipulating and finding information about the file store (such as *ls, rm* and *cd*). Comparison of other commands capture the differences between the groups. The emphasis on programming by both our novice and experienced subjects is reflected by the various compilers used (*pix* and *pi* for Pascal, *make* for "C", and *ada*). The non-programmers, on the other hand, seem concerned with word processing (as indicated by the relatively heavy use of *nroff* and *spell*). The

[4] Although similar results seem to apply to the top 10% of the command set, the recursive property of the rule cannot be checked reliably. Limits are quickly reached over the relatively small number of remaining commands.

Groups from the Current Study										Others	
All Subjects		Novice Programmers		Experienced Programmers		Computer Scientists		Non-Programmers		Hanson's Group	
command	% used	command	% used	command	% used	command	% used	command	% used	command	% used
ls	13.33	pix	25.64	ls	12.76	ls	15.75	ls	18.53	cd	12.30
cd	8.83	umacs	20.89	cd	12.03	cd	10.62	emacs	12.35	ls	10.0
pix	6.69	ls	8.18	e	6.29	e	5.58	cd	9.56	cat	9.6
umacs	5.34	rm	3.55	fg	4.42	fg	4.32	nroff	9.55	|	6.2
e	4.47	u	3.19	more	3.49	rm	3.21	e	6.20	vi	5.9
rm	3.35	cat	2.79	make	2.93	mail	3.00	rm	4.66	ed	5.6
emacs	3.28	more	2.63	rm	2.93	emacs	2.58	ee	4.47	rm	3.8
fg	3.07	cd	2.61	emacs	2.66	lpq	2.36	lpq	2.25	;	2.7
more	2.51	script	2.49	l	2.02	more	2.06	ps	2.13	>	2.5
lpq	2.02	lpr	2.26	cat	1.96	ps	1.97	cp	1.66	Mail	2.0
mail	1.95	cp	2.09	lpr	1.91	f	1.70	ptroff	1.65	nroff	1.5
cat	1.89	lpq	2.08	ada	1.85	cat	1.62	more	1.59	mail	2.0
lpr	1.49	emacs	1.95	ex-vax	1.85	who	1.59	w	1.50	mv	1.2
cp	1.48	pi	1.54	cp	1.58	mv	1.20	mail	1.37	grep	1.2
ps	1.36	p	1.21	rwho	1.37	man	1.18	rr	1.31	col	0.9
who	1.14	fred	1.04	a.out	1.33	rlogin	1.05	tbl	1.27	echo	0.9
make	1.08	mail	1.03	mail	1.31	cp	1.02	spell	1.27	&	0.9
nroff	1.06	pdpas	0.72	lpq	1.31	fred	0.99	mv	1.20	tail	0.7
fred	0.95	logout	0.71	ps	1.30	lpr	0.91	ed	1.02	pwd	0.7
man	0.90	pdp60	0.67	who	1.16	page	0.90	apq	0.89	awk	0.7
commands executed	287736	commands executed	73288	commands executed	70234	commands executed	119557	commands executed	24657	commands executed	9934
different commands	1307	different commands	264	different commands	588	different commands	851	different commands	196	different commands	400
sample size	168	sample size	55	sample size	36	sample size	52	sample size	25	sample size	16

Table 3.1: Command distributions of the top 20 commands for five different user groups

type of editor also indicates group differences — *vi* and *ed* are chosen by Hanson's group, while *emacs, e, umacs, fred,* and *ed* have varying degrees of use within the others.

Grouping all subjects into one category also illustrates the danger of using a population stereotype to approximate the activity in each group. As shown by column 1 of Table 3.1, which pools all subjects of this study into one large sample, some high-frequency commands are not used frequently (if at all) by all groups (*eg pix, umacs*).

Even though the Zipf form of the frequency distribution remains intact between different groups of a population (Figure 3.1), the rank order of commands is not, in general, maintained.

3.3 Frequency distributions and command overlap between individuals

The extent to which the usage statistics of an individual resembles those of a group of like people is considered next. Does the Zipf distribution characterize each user's command interactions, or is it just an artifact of data grouping? Do individuals within a group invoke the same set of commands? One might expect the variation between users to be even greater than that between groups.

In the previously-mentioned study of the UNIX on-line manual, the frequency distribution of help requests was analysed between individuals (Greenberg, 1984). In general, users constrained themselves to relatively small subsets of the requests possible — they never accessed a great many potential entries. Moreover, when users' subsets were compared, the intersection between their elements was small and the frequency of access of the common elements varied considerably across users. Greenberg (1984) suggested that although individual help requests seem to follow the Zipf distribution in broad outline (but not in detail), it is not possible to make any but the grossest generalization from a population perspective of how individual users will access particular items within a system. This study is summarized further in Section 5.3.1.

The same is true for command line interactions. While studying the nature of expertise in UNIX, Draper (1984) estimated the times a command was invoked by noting the UNIX processes spawned during each user's interaction with the system (method 4 → §2.2.1)[5]. He suggested that the overall trends observed are representative of real command use. First, out of a vocabulary of the 570 commands available to the population, only 394 (70%) were used at least once. Individuals knew the system to varying degrees — there was a fairly smooth distribution of vocabulary size up to the maximum of 236 commands known to one user. Characteristics of the overlap between individuals' vocabularies were similar to those found by Greenberg (1984). Generally, very few of each individual's commands were used by all the population, a few more shared to some degree by other users, and the rest used by him or her alone. Draper concluded that vocabulary is a poor measure of expertise, and that each user is actually a specialist in a particular corner of the system.

Sutcliffe and Old (1987) pursued the matter further in a similar study by ranking commands by popularity. They established that the top twenty commands accounted for 73% of the overall number recorded. The remaining 27% accounted for 236 further commands. However, these results may be misleading, for heavy use of a command by an individual will skew the distribution.

Even though Draper's method of data collection differed, this study corroborates his conclusions. The first ten rows of Table 3.2 show the proportion of commands shared by the users comprising a particular group. The following rows show the proportion of commands that are not shared, the total number of different

[5]Sutcliffe and Old (1987) employed the same method to replicate portions of Draper's work. Their findings are similar throughout.

commands entered by each group, and the average number of different commands per user. Table 3.3 lists the twenty most shared commands for each user group. For example, only 0.2% (*ie* 3) of the 1307 different commands used by all subjects were shared by more than 90% of them (these were basic file manipulation commands for listing, removing and copying files, as shown in column 1 of Table 3.3). More surprisingly, fully 92% of all commands were shared by fewer than 10% of the users, and 68.8% of all commands are not shared at all. These differences are much stronger than those suggested by Draper's group (the last column of Table 3.2), probably due to inaccuracies in his estimate of command use.

Tables 3.2 and 3.3 also reveal that categorizing like subjects into groups changes the figures less than one might expect. For example, even though individuals in the novice group used the system for solving the same programming assignments and were taught UNIX together, there was relatively little intersection of their vocabularies. Except for a handful of commands, users — even those with apparently similar task requirements and expertise — have surprisingly little vocabulary overlap.

3.4 Growth of the command vocabulary

In the previous discussion, a user's vocabulary was taken to be the set of commands he invoked over a fixed period of time. But how dynamic is the command vocabulary of a user? Do users learn new commands sporadically or uniformly over time? Are new commands acquired continually, or do users stop acquiring new vocabulary after some initial period?

Sutcliffe and Old (1987) suggest that the size of user's command set grows with their system usage. They found a significant correlation between the overall command use by the user and the number of unique commands he employed. This evidence is suggestive but does not actually observe vocabulary acquisition

% of users sharing a command	Proportional Number of Commands Shared (%)					
	All Subjects	Novice Programmers	Exper'd Programmers	Computer Scientists	Non Programmers	Draper's Group
100–91	0.2	2.7	2.2	0.9	1.5	0.5
90–81	0.3	0.8	0.7	0.8	0	2.0
80–71	0.3	0.4	1.0	0.8	2.0	3.1
70–61	0.4	0.8	1.0	0.6	0.5	3.3
60–51	0.5	1.5	2.2	1.9	4.6	3.1
50–41	0.5	2.7	1.9	1.1	3.1	6.1
40–31	1.2	0	1.2	1.4	4.6	6.1
30–21	1.5	9.1	4.1	4.4	6.6	8.6
20–11	3.0	12.1	8.9	6.5	34.7	17.8
10–0	92.0	70.1	76.9	81.7	42.4	49.5
not shared	68.8	55.3	58.5	63.1	42.3	unknown
Total number of unique commands						
	1307	264	588	851	196	394
Mean number of unique commands per subject and standard deviation						
mean	50.3	27.8	66.4	72.1	29.6	unknown
std dev	32.5	18.0	24.9	32.7	20.1	unknown

Table 3.2: Number of users per command

The 20 Most Shared Commands									
All Subjects		Novice Programmers		Experienced Programmers		Computer Scientists		Non-Programmers	
command	# of users	command	# of users	command	# of users	command	# of users	command	# of users
ls	168	lpr	55	cd	36	ls	52	ls	25
rm	164	ls	55	ls	36	rm	51	rm	24
cp	154	pix	55	more	36	cat	50	emacs	23
lpq	149	rm	55	lpq	35	cd	50	cd	19
lpr	144	script	55	man	35	mv	49	cp	19
cd	141	cp	53	cat	34	cp	48	nroff	18
cat	140	lpq	53	cp	34	mail	48	lpq	17
mail	131	umacs	47	lpr	34	man	48	ps	16
more	130	cat	46	mail	34	mkdir	46	lpr	14
man	124	more	42	mkdir	34	ftp	44	more	14
who	117	cd	36	rm	34	lpq	44	logout	13
mv	114	mail	36	ftp	33	ps	44	mail	13
emacs	112	limits	32	ps	32	pwd	44	man	13
mkdir	104	who	30	mv	31	who	44	hpq	12
ps	103	man	28	who	31	fg	42	mv	12
fg	95	pi	28	ruptime	30	e	41	spell	12
script	95	logout	26	fg	29	emacs	41	who	12
pwd	92	help	24	kill	28	lpr	41	kill	11
ftp	91	lquota	23	limits	28	rlogin	40	pwd	11
logout	88	emacs	23	rwho	28	kill	38	cat	10
sample size	168	sample size	55	sample size	36	sample size	52	sample size	25

Table 3.3: The 20 most shared commands for each user group

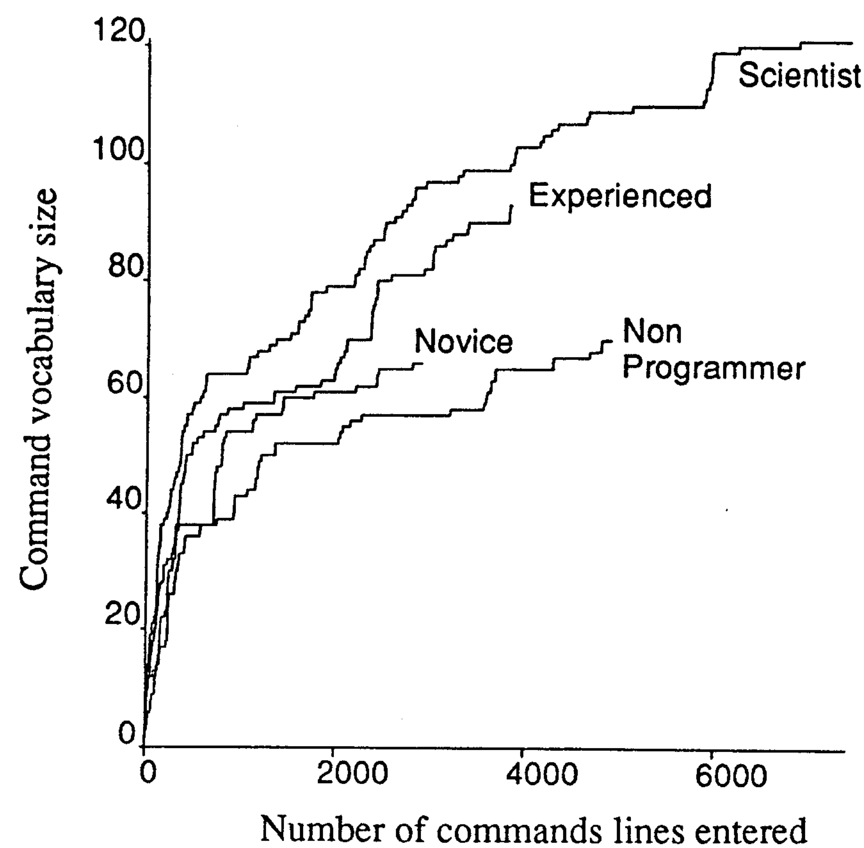


Figure 3.2: Command vocabulary size versus the number of command lines entered for four individuals

by particular users. Figure 3.2, on the other hand, illustrates the acquisition of vocabulary over time for four typical users from the current study, one from each group. The vertical axis is vocabulary size, while the horizontal axis represents the number of command lines entered so far. At first, the vocabulary growth rate seems to be around 5% — each user shown here has a repertoire of 43 – 64 commands after 1000 full command lines had been entered. But the growth rate drops quickly afterwards to 1% or less. The later part of the curve is probably a better reflection of vocabulary acquisition, for the first part does not necessarily reflect a learning curve. Since users already knew a command subset before monitoring began, unusually high initial activity is expected as known commands are being noticed for the first time. Another explanation is that the curve just represents the arrival probability of infrequent commands whose distribution patterns follow Zipf.

Although Figure 3.2 suggests that the selected subjects have a vocabulary growth rate which is proportional to the relative sophistication of the group, analysis of variance shows no statistically significant differences between the mean rate of each group. However, these rates were determined by counting the new commands acquired between 1000 and 2000 command entries, which meant excluding those subjects who did not have at least 2000 entries.

Figure 3.2 also reveals how users acquire new commands. Although there are short periods where vocabulary growth is relatively uniform, there are also long periods of quiescence followed by a flurry of activity. As might be expected, these flurries were sometimes associated with new tasks. For example, the sharp increase in new activity for the Scientist subject after she had entered 6000 command lines all involved high-quality typesetting (Figure 3.2). However, there are other instances where no such task association is evident.

In general, individuals have small command vocabularies and acquire new ones slowly and irregularly. Given the patterns observed, the Zipf distribution becomes a questionable model of individual command use. Perhaps all that can be said is that the distribution of command use is very uneven.

3.5 Relations in command sequences

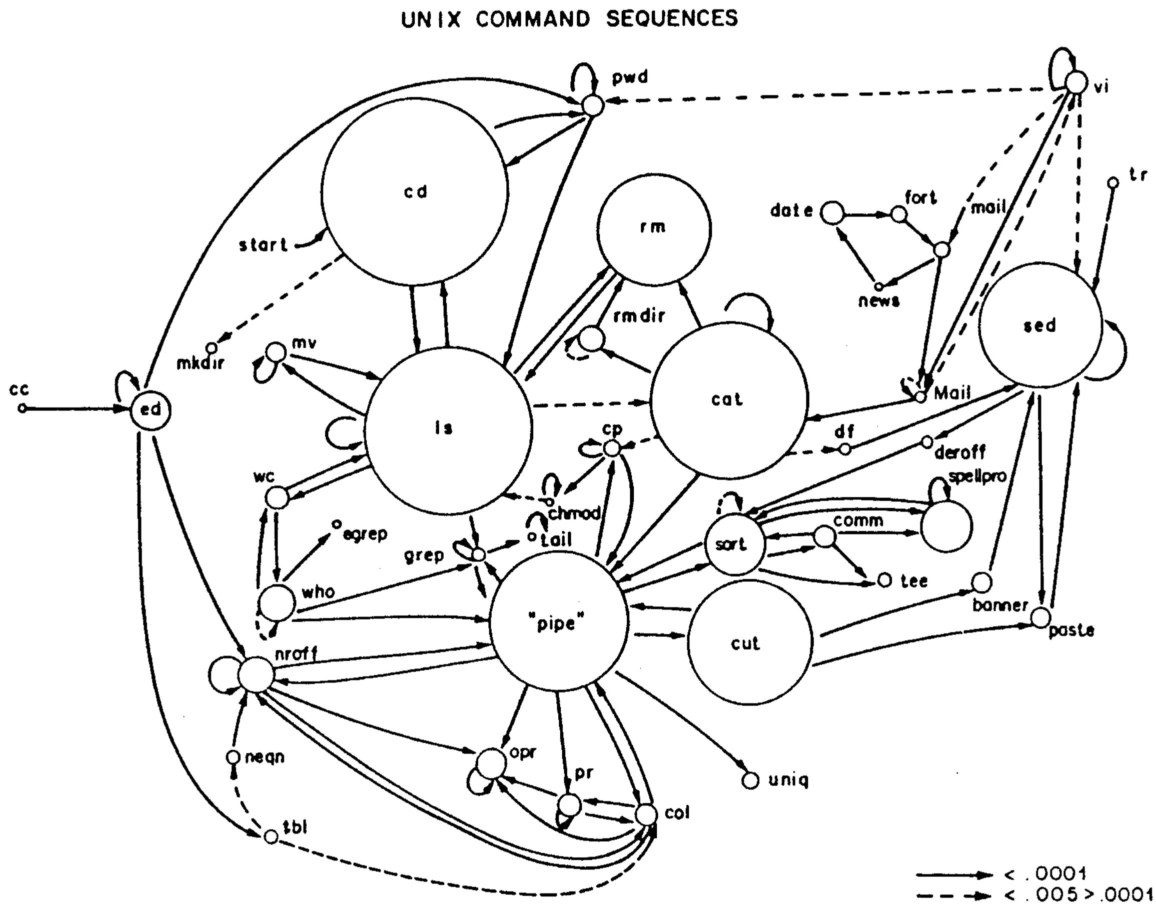
The previous discussion says nothing about possible relations and dependencies between commands. Through a multivariate analysis of UNIX commands invoked by the site population, Hanson *et al* (1984) examined the interaction effects between commands. Their results show statistically significant relationships between certain command chains; the relations between the 50 most frequently used commands are shown in Figure 3.3. Each ball in the network represents a command, its size indicates the usage frequency, and the arrow indicates the significant dependencies. One dimension of these relationships is *modularity*. Some commands, such as *ls*, are core commands — they are used frequently and are surrounded by many other commands (ie highly modular and independent). Others are not; they are surrounded by specific command sequences. An example of the latter is *cp* which is generally preceded by itself and followed by *chmod*.

Commands are also related by functional clusters, such as editing, process management, orientation, social communication, and so on (Hanson *et al*, 1984), which may not be revealed by statistics. Consider a user who prints files in several ways: a short draft may go to the screen; a long listing to a lineprinter; and a final version to a laser printer. Although these non-sequential and possibly rarely invoked actions are related by function in the user's mind, it is unlikely that such a relationship would appear from a multivariate analysis of commands like Hanson's. Additionally, it is a mistake to assume that all dependencies revealed by analyzing a group of users will hold for an individual, since each person uses their own particular subset of commands → §3.3.

3.6 Discussion

The previous sections reviewed statistics from studies of how people use commands in command-based systems. The purpose behind most of the original works was to derive implications for the interface design. Yet it is clear that statistics produced by pooling users into one large sample are not necessarily indicative of an individual's statistics. As a consequence, some of the conclusions made by the original researchers are misleading.

First, the rank frequency distribution of a population should not be applied to



Ball diameters are proportional to stationary probability. Lines indicate significant dependencies, solid ones being more probable ($p < .0001$) and dashed ones less probable ($.005 < p < .0001$).

Figure 3.3: Sequential structure of Unix command usage, from Figure 4 in Hanson *et al* (1984)

an individual. Careful interpretation must be used before following the advice of one researcher, who says "the Zipf distribution may prove to be a useful model of user behaviour in studying command usage" (Peachey *et al*, 1982). It is all to easy to read into such a statement two implications. First, the Zipf model is a reasonable estimate for a single person's frequency of command use. Second, the rank order derived from a population applies to an individual. These are certainly not the case. Next, and more specifically, Hanson *et al* recommend that commands used frequently by the population should be treated differently:

> ...the uneven distribution of command use suggests that computer systems should find ways to increase the prominence and ease of access to frequently used commands.
>
> — Hanson *et al*, 1984

Given the results of the previous sections, this should more correctly read "...to increase the prominence and ease of access to an *individual's* frequently used commands". The slight wording difference is crucial. Whereas the original conclusion implies that command prominence may be judged and treated generically, the corrected version would require a personalized approach.

Second, it is a mistake to assume that users have similar vocabularies. Hanson *et al* (1984) went on to say that computer systems should be organized with sets of frequently used core commands, implying that these sets are reasonably large and that core commands are shared. But the findings detailed in Section 3.3 refutes this prescription in two ways. First, individuals have very few common commands. Second, people may use different resources for implementing those few actions they have in common, *eg* different editors and compilers for text processing and programming respectively. Sutcliffe and Old explain these phenomena.

> Considering UNIX is a system rich in functionality but relatively unstructured, it is not surprising [that] users have created a variety of tasks

> with the tools available ... great creativity is exercised in implementing a rich diversity of tasks.
>
> — Sutcliffe and Old, 1987

Perhaps the few shared and frequently used commands could best be handled as exceptions, possibly by bundling them into a finely-tuned application. For example, the extremely heavy use by all users of the basic file manipulation commands, as noted in Tables 3.1 and 3.3, suggests that users require not only constant feedback on the contents of the current directory, but some simple tools for manipulating them as well. Feedback can be provided by keeping a permanent display of the current files on view, a simple task given a window-based environment. If screen real-estate is a concern, transient windows popped up by a mouse press may be used instead (Greenberg *et al*, 1986). These findings also support the inclusion of the more sophisticated file browsers that are found in many modern programming environments.

Third, the relations between commands seen by Hanson's pooled statistics do not necessarily apply to individuals→ §3.5. The dependencies and clustering observed may result from a small handful of people using a set of related commands frequently, and not from common use of the same commands by every person. Consider the recent findings of Sutcliffe and Old (1987). They replicated and extended Hanson's work by eliminating all dependencies but those that were significant for at least five or more individual users (*cf* Figure 3.3). The resulting network was a fragmented subset of the population network. Sutcliffe and Old concluded that only a small number of commands were used in common tasks by a majority of individuals. Hanson, then, has insufficient evidence for suggesting that

> ...it would be practical to organize the commands around task-related menus. Commands that are likely to be used in one context may also be needed in others.

— Hanson *et al*, 1984

To their credit, Hanson *et al* also state that such menus are best viewed as default organizations which, due to individual differences, should be customizable by the user.

In another area, many intelligent tutoring systems and the models they employ are motivated by possibly incorrect assumptions of command usage. Consider Hecking (1987), for example, who quotes the statistic "people use only 40% of all UNIX functions" (*cf* Draper's 70%→ §3.3). He claims that this situation is a poor one and advocates intelligent help systems as a remedy. Yet Draper (1984) contradicts this claim by suggesting that users are best viewed as specialists in their own corner of the system. Next, consider how expertise models are formed. One approach for deciding what knowledge should be presented to the user employs an "expert" and a "student" model (Sleeman and Brown, 1982). For example, the *differential* model of Burton and Brown (1982) bases its instructional presentation on the differences between a student's and an expert's behaviour, and has been advocated in the UNIX domain (Chin, 1986). Desmarais and Pavel (1987) use a similar model to generate knowledge structures of commands. These structures indicate the likelihood that an observed command has been mastered by a person, and are used to infer what other commands he might know. Another expertise-based strategy is employed by the well-known UNIX Consultant, which stereotypes users into one of four levels of expertise and tailors its advice to them accordingly (Chin, 1986). But the above approaches are ill-founded. Experienced users of general purpose environments such as UNIX do not share particular command sets. Excepting the very few in common, it is not possible to decide what commands should be offered to the student. Consequently, the differential model is not necessarily appropriate for teaching people how to use general-purpose computer systems.

Concluding Remarks

This chapter has surveyed and replicated studies in several areas involving user interactions with command-based computer systems. The trends observed are presumed to be shared by most command-based interactions; they are not just artifacts of the UNIX implementation. The major findings follow.

1. The rank frequency distribution of command usage by groups of like and unlike users is approximated by a Zipf distribution.
2. With a few exceptions, the frequency of use of most commands differs between groups — rank order is not maintained.
3. There is little overlap between the command vocabulary of different users, even for those with apparently similar task requirements and expertise.
4. Individuals have small command vocabularies, and new commands are acquired slowly and irregularly. Consequently, the Zipf model may not be an accurate estimate of an individual's behaviour.
5. Some commands cluster around or follow others in statistically significant ways, although these dependencies vary from one individual to another.

These conclusions tell us more about individual differences than about similarities, and they are not as useful as one might hope. Although they do refute some previously held beliefs, the conclusions do not suggest any general new directions in interface design.

I believe that these studies place undue attention on command usage. The reductionist approach may have been pushed too far. Commands, after all, are only the verbs of the command line. They also act on objects, are qualified with options, and may redirect input and output to other commands. These other facets are surely important and should not be ignored. For example, UNIX lines sharing the same initial command may have completely different meanings. Consider the two command lines *sort file* and *sort file* | *uniq -c* | *sort -r*. The first just sorts a file, while the second produces a frequency count of the identical lines in the file. Another problem is that the same command line may satisfy rather different intentions. Ross *et al* (1985) give an example of one person invoking the UNIX command line *ls -l* to distinguish between ordinary files and directories, whereas another person could use the same sequence to discover file creation dates and sizes. Accordingly the UNIX usage data, analyzed in this chapter in terms of commands, is re-analyzed in Chapter 5 in terms of command lines.

How does all this fit into tool use, the theme of Chapter 1? If only commands are considered to be tools, then the tool set chosen by each user does not seem particularly rich. Few are selected, and of these only a handful are used to any great extent. Alternatively, if commands are viewed as simple building blocks used to manufacture more sophisticated or specialized tools — perhaps by reshaping (setting options), combining them together (redirection, pipelines and sequencing), or by varying the objects they deal with — then every unique command line entered can be considered a new tool. The latter view is espoused by the remainder of this document.

I will argue that, as with tools, the work environment should support and enhance the way people use complete command lines. Recently used submissions should be available for reuse, and people should be able to organize their command lines by function and by task. The next four chapters of the dissertation consider the first strategy — reuse. Afterwards, Chapter 8 considers the ways people organize their activities, while Chapter 9 describes an implemented design of a user support tool that allows people to reuse and store command lines (as they do tools) through a workbench metaphor.

Chapter 4

Techniques For Reusing Activities

It is evident that users often repeat activities they have previously submitted to the computer. These activities include not only the commands they choose from the many available in command-driven systems (Chapter 3), but also the complete command line entry. Similarly, people repeat the ways they traverse paths within menu hierarchies, select icons within graphical interfaces, and choose documents within hypertext systems. Often, recalling the original activity is difficult or tedious. For example, problem-solving processes must be re-created for complex activities; command syntax or search paths in hierarchies must be remembered; input lines retyped; icons found; and so on. Given these difficulties, potential exists for a well-designed "reuse facility" to reduce the problems of activity reformulation.

But most system interfaces offer little support for reviewing and reusing previous activities. Typically they must be completely re-typed, or perhaps reselected through menu navigation. Those systems that do provide assistance offer *ad hoc* "history" mechanisms that employ a variety of recall strategies, most based on the simple premise that the last *n* recent user inputs are a reasonable working set of candidates for re-selection. But is this premise correct? Might other strategies work better? Indeed, is the dialog sufficiently repetitive to warrant some type of activity reuse facility in the first place? As existing reuse facilities were designed by intuition rather than from empirical knowledge of user interactions, it is difficult to judge how effective they really are or what scope there is for improvement.

The next four chapters of this document explore the possibility of people reusing (as opposed to re-entering) their previous activities. This chapter surveys and provides examples of interactive reuse facilities that allow users to recall, modify, and re-submit their previous entries to computers. Although the idea is simple — anything used before can be used again — it is only effective when recalling old activities is less work for the user (cognitively and physically) than submitting new ones. As we shall see in this chapter, the main differences between reuse facilities arise from their ability to offer a reasonable set of candidates for reselection, and from the user interface available to manipulate these candidates.

For example, consider a user who has submitted n activities to the system (say $n > 100$) and whose next activity is identical to a previous one. An optimal reuse facility would be an oracle that correctly predicted when an old action could be reused and submitted it to the system in the user's stead. In contrast, a non-predictive system that merely presents the user with all previous n submissions would be less effective, for the user's overhead now includes scanning (or remembering) the complete interaction history and selecting the desired action. Real systems are situated between these extremes. A small set of reasonable predictions p is offered to the user ($p << n$), sometimes ranked by probability. The intention is to make the act of selecting a prediction less work than entering it anew; the metric for "work" is, of course, ill-defined.

Reuse facilities have loose analogies in non-computer contexts. A cook can explicitly mark preferred recipes by using bookmarks (n = total recipes used, p = total bookmarks). "Adaptive" marking takes place by the book naturally opening to highly used locations through wear of the binding and food-encrusted pages. Or consider the audiophile who places records just listened to at the top of the pile.

Assuming that certain records are favoured over others, popular records tend to remain near the top of the stack and unpopular ones near the bottom. A carpenter's workbench has an implicit reuse facility — the work surface is large enough to leave recently used tools on hand.

Three kinds of reuse facilities are distinguished in the following sections. The first covers *history mechanisms* that let users manipulate a temporally-ordered list of their interactions. The second, *adaptive systems*, use dynamic models of previous inputs to predict subsequent ones, which are then made available to the user. Finally, *programming by example* is concerned with reuse and generalization of long input sequences.

The three subsequent chapters will assume an experimental approach to reuse. Analyses of data and discussions are focused toward seeing how people repeat their activities on UNIX and other systems, and the results are distilled into design principles for empirically-based reuse facilities.

4.1 History Mechanisms

History mechanisms are based upon the assumption that the last p submissions provide a reasonable set of candidates for reuse. This notion of "temporal recency" is cognitively attractive. Since users generally remember what they have just entered, they can predict effectively the offerings available. Little time is wasted reviewing the list of candidates only to discover that the desired item is missing.

History mechanisms are by far the most common reuse facility available, and are implemented across diverse systems in a variety of flavours. Four fundamentally different interaction styles are described in this section: glass teletypes; graphical selection; editing transcripts; and bookmarks. The first three provide a reuse facility for command-line interfaces, while the last illustrates its application to hypertext systems.

4.1.1 History in glass teletypes

Before graphical interfaces came into vogue, dialogues were simple command-line systems designed for the teletype — the VDU being a fixed viewport into a virtual roll of paper. Two functionally rich history systems designed for such physically limited "glass teletypes" are the UNIX *csh* and the INTERLISP-D Programmer's Assistant. In both systems, old commands are retrieved by "history" directives, themselves commands interpreted in a special way.

UNIX *csh* maintains a record of user inputs, where every string entered on the command line is placed on a numbered event list (Joy, 1980). Special syntactic constructs allow previous events to be recalled, either by position on the event list (relative or absolute), or by pattern-matching. Actions on recalled events include viewing, re-execution, retrieval of specific command line words, and text substitution. Although the set of predictions is unbounded in size, it is practically small — users forget all but the last few items, and reviewing a long list is cognitively unattractive.

Figure 4.1 illustrates a possible event list and a few examples of *csh* history in use. The inputs in the left column are translated by *csh* to the actions shown in the middle. The translation is described in the column on the right. As the examples illustrate, the syntax is quite arcane, and probably deters use of the more powerful features. Additionally, since the event list is generally invisible — snapshots of its current state are displayed only by special request — it is difficult to refer to any but the last few events.

Another functionally powerful history mechanism is the Programmer's Assistant, designed for the INTERLISP-D programming environment (Teitelman and Masinter, 1985; Xerox, 1985). Although INTERLISP-D is window-based, the top-

Example Event List
9 mail ian
10 emacs fig1 fig2 fig3
11 cat fig1
12 diff fig*

Examples and Results of History Uses		
User Input	**Action**	**Description**
!!	diff fig*	Redo the last event
!11	cat fig1	Redo event 11
!-2	cat fig1	Redo the second event from last
!mai	mail ian	Redo last event with prefix "mail"
!?ian?	mail ian	Redo last event containing the string "ian"
!! fig3	diff fig* fig3	Append "fig3" to the last event and redo
∧diff∧page	page fig*	Substitute "page" for "diff" in the last command
!!:p	diff fig*	Print without executing the last event
page !10:1-2	page fig1 fig2	Include the 1st and 2nd argument of event 10 and redo

Figure 4.1: Examples of the UNIX *csh* History Mechanism in use

level "LISP listener" window resembles a glass teletype. The Programmer's Assistant history mechanism improves upon that of UNIX *csh*. More than one event can be retrieved and manipulated at a time, iteration and conditional specification are allowed, items can be edited, effects of previous entries may be undone, and so on. In normal use, events are selected and processed by special command directives entered in the LISP listener window. These tend to be verbose. For example, the request *USE cons FOR setq IN -1* will replace the string "setq" by the string "cons" in the previous command. Figure 4.2 shows a sample dialog in the window labeled "Interlisp-D Executive", where events 85 and 87 make use of the Programmer's Assistant. As with *csh*, neither duplicates nor erroneous statements are pruned from the event list.

4.1.2 History through graphical selection

The technology of terminals has evolved since the early glass teletypes. All but the cheapest terminals now have positional control of text on the screen, and high-resolution graphics terminals with locators are common. Interaction styles have also progressed from text-oriented menus and forms to locator-oriented graphical systems running within windows (Witten and Greenberg, 1985). Within the latter, history mechanisms have been extended to present a (possibly transient) menu of previous events. Items are selected and manipulated with a locator, usually a mouse. In contrast to glass teletype history, predictions are offered by presenting them explicitly on the screen.

One example is HISTMENU, which provides a limited yet simple way of accessing and modifying the INTERLISP-D Programmer's Assistant history list (Bobrow, 1986). Figure 4.2 illustrates its use. Commands entered to the INTERLISP-D Executive window are recorded on the history list, part of which is displayed in the History window (by default, the last 50 items are shown). Although the history list itself is updated on every command, the window is only redrawn when the user explicitly requests it. When pointed at with a mouse, items (which may not fit completely in the narrow History window) are printed in the Prompt window. Any entry can be re-executed by selecting it. Moreover, a pop-up menu allows limited further action: items can be "fixed" (*ie* edited); undone; printed in full including additional detail (the "??"); or deleted from view. The History window also has a shrunken form, as shown by the icon in the Figure.

MINIT is another graphical package that combines command processing and the history list into a single "window management window" (*wmw*) (Barnes and Bovey, 1986). MINIT differs from other systems in that only through this window can the user send commands to the other ones. The *wmw* is divided into three regions. The first is an editable typing line at the window's bottom, where commands are entered. Once entered, they are added to the second region which contains a scrol-

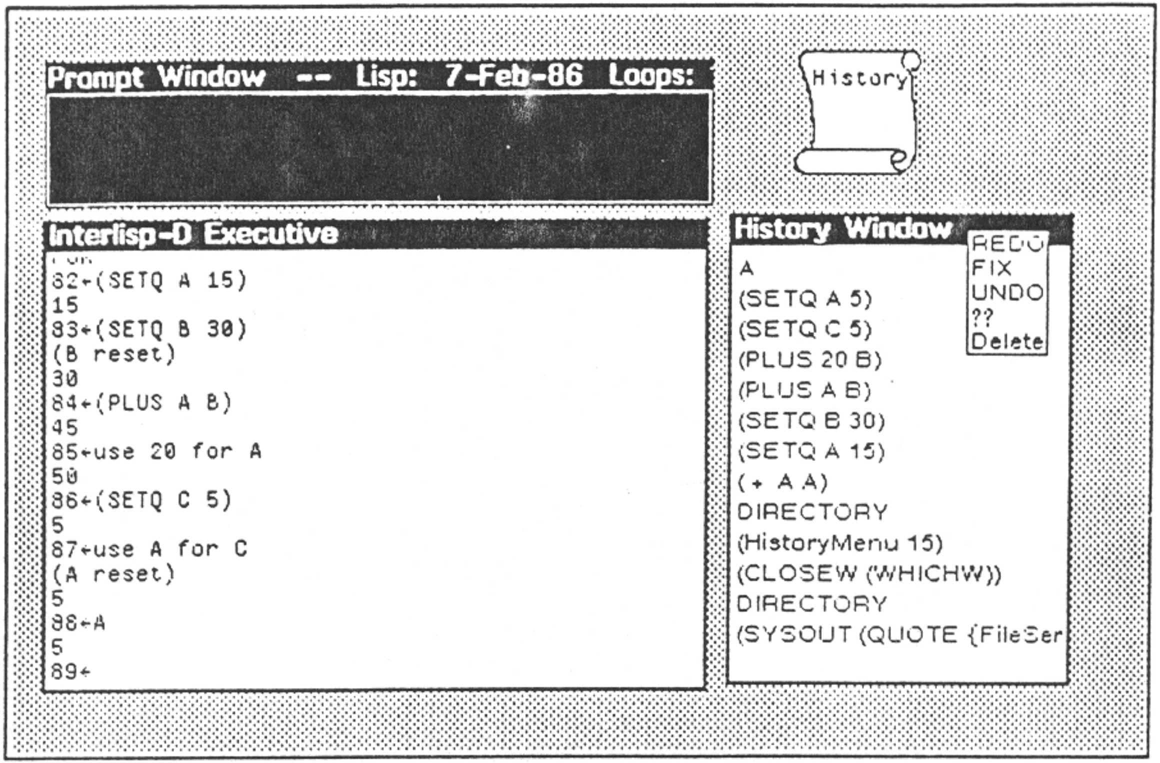


Figure 4.2: A portion of the INTERLISP-D environment, showing HistMenu in use

betical or execution order. Although duplicate lines are eliminated, the user can control whether a command entry which is repeated remains in its original position on the execution-ordered list or is relocated to the end. A side effect of moving recurrences to the end is that the most frequently used commands tend to cluster around one another.

4.1.3 History by editing transcripts

Some systems do not have a command history mechanism *per se*, but provide similar capabilities through editing the transcript of the dialog.

The glass teletypes described previously are actually more limited than paper teletypes, for it is not possible to review text that has scrolled off the screen. This limitation is exacerbated by high-speed terminal lines, for text appears and disappears faster than it can be read. Although page-holding mechanisms that stop scrolling after every screenful offer a palliative, the advantages of the original paper teletype were finally realized when scrollable transcripts of the dialog were maintained[1]. Unlike paper teletypes, these transcripts have potential as a history mechanism, for text appearing previously can be pointed at and used as input to the system.

In Apollo's DOMAIN window system, for example, text appearing within specialized windows called "pads" can be copied and then pasted and edited in any command input area (Apollo, 1986). Explicit history lists are not maintained except as part of the scrollable dialog transcript. The trade-off here is evident. Although *any* text in a pad is potentially executable, the mixing of previous input commands with output probably makes useful candidates difficult to find.

[1] An alternative solution to transcripts is to make every system facility responsible for formatting its output appropriately. The tradeoff between the two approaches is discussed by Pike and Kernighan (1984).

A second system which encourages use of command history through editing is *emacs*, an editing environment which provides multiple views of buffers through tiled windows (Stallman, 1981). Although buffers typically allow users to view and edit files, it is also possible to run interactive processes (or programs) within them. In the Unipress implementation of *emacs*, it is a simple matter to call up a window running UNIX *csh* (Unipress, 1986). All capabilities of *emacs* are then available — commands may be edited, sessions scrolled, pieces of text picked up from any buffer and used as input, and so on.

As a further variant, consider the *zmacs* editor running within the Symbolics Genera LISP environment, which contains features of all history systems discussed so far (Symbolics, 1985). Within the top-level Lisp Listener, *zmacs* extends the functionality of *emacs*. Although used here primarily for entering and editing command lines, previous inputs appearing within the transcript become mouse-sensitive. A box appears around them as the mouse passes over them, while clicking one of the three mouse buttons causes some action to occur. For example, pressing the left button of the mouse over the old command line copies it into the input area, which is then available for further editing. Other combinations of keys immediately re-execute previous commands, copy arbitrary command words, show documentation, and so on. And *zmacs* explicitly remembers previous events on an event list. Using the standard editing commands within the one-line input area, a user can search, cycle through, and recall previous events. Alternatively, part or all of the mouse-sensitive event list can be displayed within the Lisp Listener window.

4.1.4 Bookmarks in hypertext

While the above techniques deal only with command-line interfaces, history has also been applied to data bases where items are retrieved through menu navigation.

There are many examples of systems and databases where users tend to retrieve items of information that have been accessed previously (Greenberg and Witten, 1985a). As with commands, the actual sets of items retrieved by different users may be disjoint, overlapping or identical; while the frequency of repeated accesses can exhibit high variation across users and across entries. History for hypertext systems, for example, are based on the assumption that previously-read documents are referred to many times. This assumption has been supported by a study of *man*, the UNIX on-line manual → §5.3.1 (Greenberg, 1984). Each user frequently retrieved the same small set of pages from the large set available, where sets differed substantially between users. By keeping a history list of the documentation retrieved, users can avoid re-navigating the hypertext menu hierarchy for a previously viewed topic. Since items on the list can be viewed as place-holders in a large document, they are known as "bookmarks".

The Macintosh HyperCard is a hypertext facility that allows authoring and browsing of stacks of information comprised of cards. Browsing cross links between stacks and cards is usually accomplished by simple button or menu selections. *Recent* is a bookmark facility within HyperCards that maintains a pictoral list of up to the last 42 unique cards visited (Figure 4.3). Each picture is a miniature view of the card, placed in the list by order of first appearance[2]. The last card visited is distinguished by a larger border, as illustrated by the second miniature in the first row of the Figure. A pull-down menu option pops up the *recent* display, and old cards are revisited by selecting its miniature from the list (Good *et al*, 1987). When more than 42 unique items have been selected, the first row of seven items is cleared and made available for new ones (even though a card in the first row may have recently been selected).

The Symbolics environment includes a very large on-line manual viewable with the Document Examiner — a window-based hypertext system (Symbolics, 1985).

[2]Figure 4.3 is a fairly accurate representation of the screen. As these miniature pictures are of surprisingly poor quality, the value of the current *recent* implementation is questionable. However, this problem could be overcome by a higher-resolution display or by including a "magnifying glass".

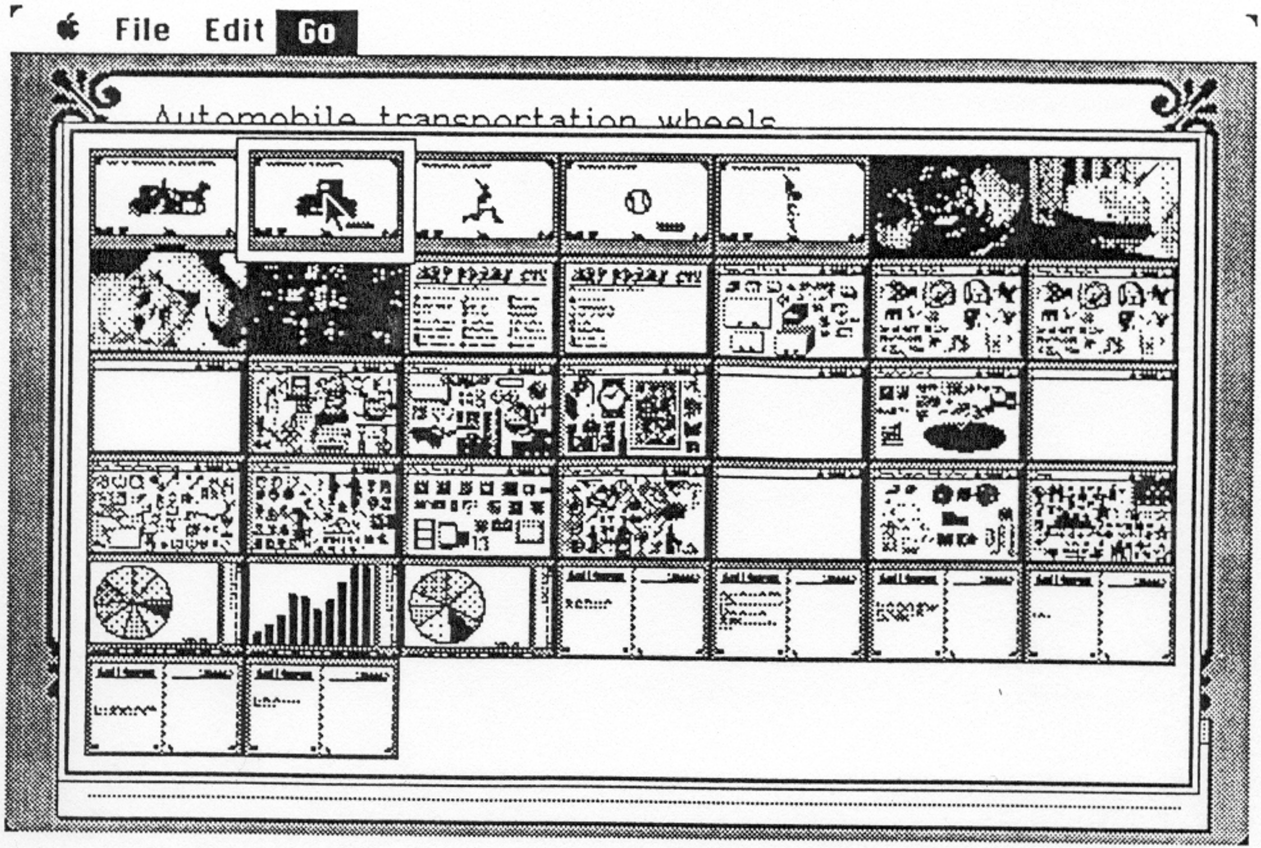


Figure 4.3: The HyperCard *Recent* screen

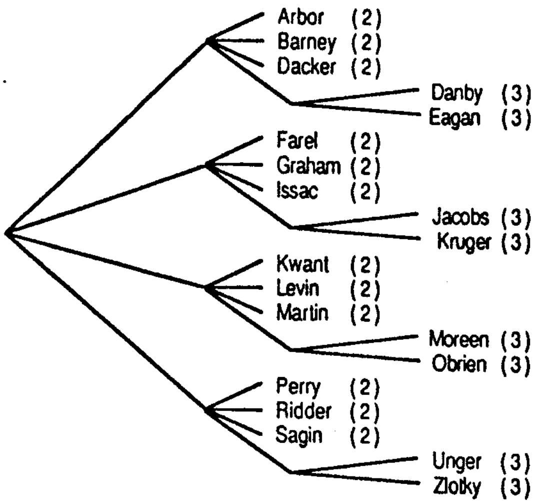
4.2 Adaptive systems

Adaptive systems use dynamic models of a user's previous inputs to predict subsequent ones, which are then made available to the user. By this definition, history mechanisms are also adaptive, since the model maintained and presented is just the time-ordered record of submissions. In this section two other types of adaptive systems are described. Both employ frequency-based, rather than recency-based, models.

4.2.1 Dynamic menu hierarchies

It is possible to devise interactive menu-based interfaces that dynamically reconfigure a menu hierarchy so that high-frequency items are treated preferentially, at the expense of low-frequency ones. This provides an attractive way of reducing the average number of choices that a user must make to select an item without adding additional paraphernalia to the interface (Witten *et al*, 1984). Consider a telephone directory where the access frequencies of names define a probability distribution on the set of entries (Greenberg and Witten, 1985a) Instead of selecting regions at each stage to cover approximately equal ranges of names, it is possible to divide the probability distribution into approximately equal portions. This reflects the "popularity" of the names selected. During use, the act of selection will alter the distribution and thereby increase the probability of the names selected. Thus the user will be directed more quickly to entries which have already been selected — especially if they have been selected often and recently — than to those which have not.

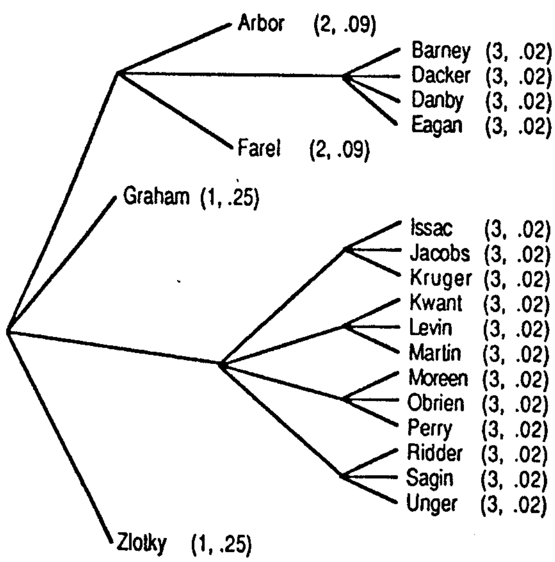
Figures 4.4a and 4.4b depict two menu hierarchies for a very small dictionary with 20 name entries and their corresponding top-level menu. Figure 4.4c calculates the average number of menus traversed per selection. In Figure 4.4a, the hierarchy was obtained by subdividing the name space as equally as possible at each stage,



a) Menu tree generated by uniform subdivision

(1) Arbor -- Eagan
(2) Farel -- Kruger
(3) Kwant -- Obrien
(4) Perry -- Zlotky

The top level menu



b) Menu tree reflecting popularity of items

(1) Arbor -- Farel
(2) Graham
(3) Issac -- Unger
(4) Zlotky

The top level menu

Let n = number of items
m_i = menus traversed to reach item i
p_i = probability that item i is selected

A) Average menus traversed by uniform subdivision

$$= \frac{\sum m_i}{n} = \frac{(12*2)+(8*3)}{20}$$

= 2.4 menus traversed / item

B) Average menus traversed by probability subdivision

$$= \sum m_i p_i$$
$$= (2*1*.25) + (2*2*.09) + (16*3*.02)$$
= 1.82 menus traversed / item

C) Theoretical optimum menus traversed with the given probabilities (4-choice entropy)

$$= -\sum p_i * \log_4 p_i$$
$$= -((12*.02*\log_4 .02) + (2*.09*\log_4 .09) + (2*.25*\log_4 .25))$$
= 1.49 menus / item

c) Calculating the average menus traversed for various conditions

Figure 4.4: Menu trees generated by uniform and probability subdivision

with a menu size of 4. The number following each name shows how many menu pages have to be scanned before that name can be found. Figure 4.4b shows a similar hierarchy that now reflects a particular frequency distribution (the second number following the name shows the item's probability of selection). Popular names, such as Graham and Zlotky, appear immediately on the first-level menu. Less popular ones are accessed on the second-level menu, while the remainder are relegated to the third level. As probabilities also decay over time, once-popular (or erroneously-chosen) names eventually drop to a low value. Depending upon the decay value, this does address some concerns about ignoring recency. For this particular case, the average menus traversed by probability subdivision are reduced from uniform subdivision, although not as much as is theoretically possible (Figure 4.4c).

Given a frequency distribution, it is a surprisingly difficult problem to construct a menu hierarchy that minimizes the average number of selections required to find a name. Exhaustive search over all menu trees, while possible, is infeasible for all but the smallest problems. Witten *et al* (1984) have studied the problem and describe simple splitting algorithms that achieve good performance in practice.

The novelty of dynamic menus is that previous actions are almost always easier to resubmit. Users do not have to scan a list of candidates, and screen real estate is preserved. To their disadvantage, users must now scan the menus for their entries all the time, even for those accessed frequently. Since paths change dynamically, memory cannot be used to bypass the search process. However, experimental evidence suggests that this is not a problem in practice. As long as the database of entries is very large, the benefits far outweigh the deficiencies (Greenberg and Witten, 1985a; Trevellyan and Browne, 1987).

4.2.2 Reuse through text prediction

History mechanisms and to a much lesser extent dynamic menus are influenced by the assumption that the last submissions entered are likely candidates for re-execution. They are the ones visible on the screen in graphical and editing systems, the ones most easily remembered by the user in glass teletypes, and the ones given a greater probability in dynamic menus (although this depends on the decay factor).

Two systems provide an alternative strategy for textual input — the "Reactive Keyboard" (Witten *et al*, 1983; Darragh, 1988) and its precursor *predict* (Witten, 1982). Although implementation details differ, both use a dynamic adaptive model of the text entered so far to predict further submissions. At each point during text entry, the system estimates for each character the probability that it will be the next one typed. This is based upon a Markov model which conditions the probability that a particular symbol is seen on the fixed-length sequence of characters that precede it. The order of the model is the number of characters in the context used for prediction. For example, suppose an order-3 model is selected, and the user's last two characters are denoted by 'xy'. The next character, denoted by ϕ, is predicted based upon occurrences of '$xy\phi$' in previous text (Witten, Cleary and Darragh, 1983).

Predict filters any glass-teletype package, although limited character graphics capabilities are required for its own interface. It selects a single prediction (or none at all) as the most likely and displays it in reverse video in front of the current cursor position. The user has the option of accepting correct predictions as though he had typed them himself, or rejecting them by simply continuing to type. Because only a single prediction is displayed, much of the power of the predictive method is lost; for at any point the model will have a range of predictions with associated probabilities, and it is hard to choose a single "best" one (Witten, 1982).

The Reactive Keyboard, on the other hand, has two versions of a more so-

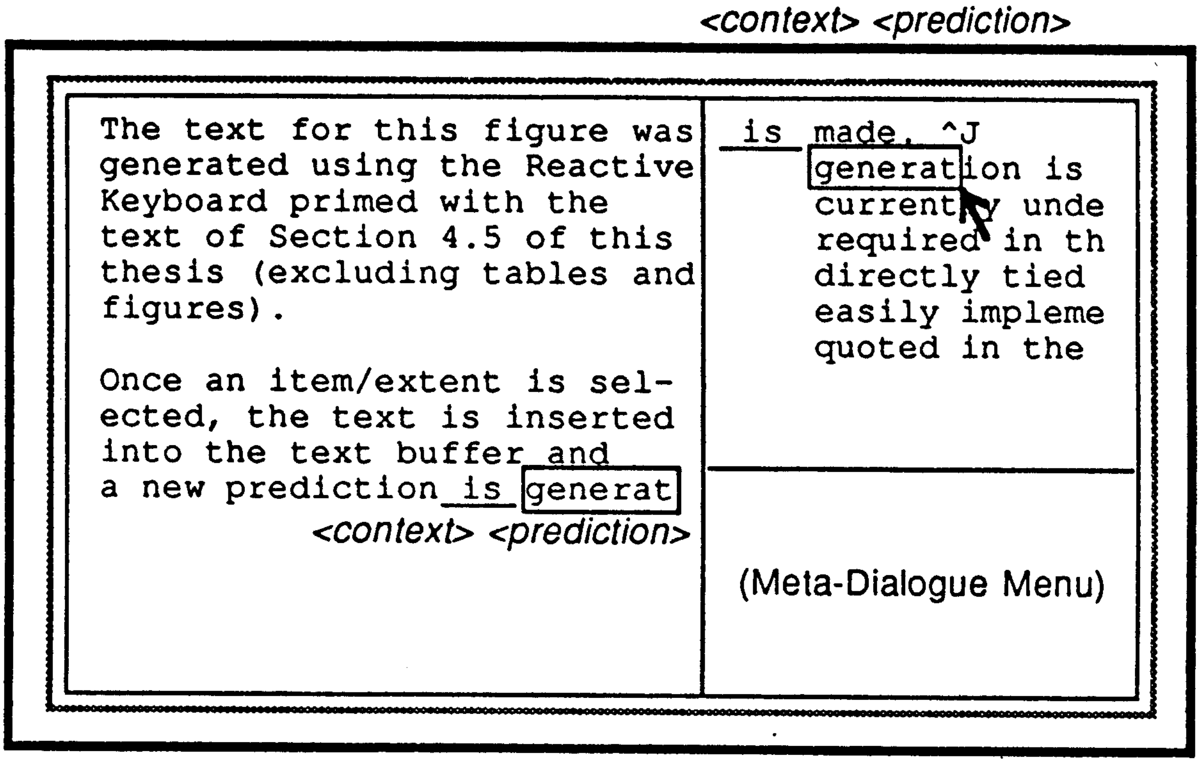


Figure 4.5: *RK-pointer* menu and feedback, from Figure 4.5 in Darragh (1988).

ticated interface that allows one to choose from multiple predictions. The first, called *RK-pointer*, displays a menu containing the best *p* predictions, which change dynamically with the immediate context of the text being entered (Darragh, 1988). Figure 4.5 shows the user composing some free text in the window on the left, and the menu of predictions on the upper right. The underlined "context" string is derived from the last few characters entered, and is followed by the highlighted best prediction. These are shown in both windows. The menu items represent alternative pieces of text from which the user can choose the next characters. Interaction is through a pointing device, such as a mouse. Selection is two-dimensional, in that the user can point anywhere within a prediction to accept only the previous characters (Figure 4.5). Less likely predictions are available through page-turning. The second version of the Reactive Keyboard is called *RK-button*, and it minimizes the screen area used by showing only one prediction next to the cursor (Darragh, 1988). Unlike *predict*, other (less probable) predictions are available through a special keystroke sequence (similar to the *zmacs* one-line history editor→ §4.1.3).

Text prediction based upon adaptive modeling appears promising. Keystroke reductions of 50% and 90% have been achieved with *predict* and the Reactive Keyboard respectively. However, these figures depend heavily on the type of text entered and how the system has been primed. Considerable variation is likely in practice. Theoretical benefits are also tempered by practical considerations. If the cognitive and mechanical task of reviewing and (perhaps) accepting predictions takes more time than simple text re-entry, then keystroke reduction becomes a misleading measure of the system's overall performance. Furthermore, as users may not be able to predict themselves the system's offerings, they must scan the list to see if a desired item is present. It is certain that a skilled typist will be capable of entering free text faster than someone using the Reactive Keyboard, for the time needed to review the predictions offered after every keystroke is far longer than the time required to just type it in. However, these are powerful systems for physically handicapped people. As Darragh notes:

> Of all potential users, those with severe physical limitations and communication disabilities stand to gain the most from the Reactive Keyboard. Certain individuals within this group will find the Reactive Keyboard a valuable time and energy saving enhancement (or replacement) for their standard communication aid when writing or accessing computer systems. (Darragh, 1988 p133)

Systems that predict character sequences are appealing because they deal with any free text. They are not limited, as history mechanisms are, to repeating lines. Yet this generality is also their weakness when used as a front end to the command-based systems addressed previously. There is no guarantee that predictions will form valid command lines, since the underlying Markov model has no knowledge about (say) UNIX. There is nothing to stop predictions from being either syntactically malformed or nonsensical.

On the other hand predictive systems have, for at least one person, proven effective for *csh* interaction. Darragh, who is partially paralysed, mentioned that *RK-button* was (and is) indispensable for his day-to-day computer use. It provided assistance on over thirty thousand command lines over a two year period, and averaged 10 character predictions per line (Darragh, 1988 p136). He also notes an interesting side effect — long descriptive file names are now used instead of short ones.

4.3 Reuse through programming by example

A difficult problem with some reuse facilities is deciding how to demarcate an activity. Ideally, an activity has a one-to-one correspondence with the task the user may wish to repeat at a later time. If activities and tasks do not correspond, then the reuse facility is not as effective as it could be. One correspondence problem is that a user's closure on a task may comprise more than one primitive activity. Closure for some of the interfaces discussed in this chapter was assumed from simple aspects of the user's input (lines, menu paths, and document selection). Yet the task one wishes to redo may be a sequence of such activities. If all were independently available through a reuse facility, the user would have to mentally decompose his task into its primitives and choose them from the event list. For example, viewing a specific UNIX file can comprise two activities — changing into the correct directory, and printing the desired file onto the screen. It would clearly be easier for the user to think about and recall these items as a single chunk rather than as two separate activities.

A second correspondence problem arises from the impracticality of recording all system primitives. A reuse facility may record only "high-level" activities, ignoring those deemed too mundane for effective reuse. But if a user's closure on a task includes some of these unrecorded sequences, the task cannot be reconstructed effectively. (Thimbleby, 1980, describes closure as the subjective sense of reaching a goal, of completion or of understanding.)

As some simple tasks are fixed sequences of activities it would be useful to save them explicitly as a procedure. A promising method for communicating this to the system is programming "by example" (Witten *et al*, 1987). At its simplest, the user performs an example of the required procedure and the system remembers it for later repetition. For example, the use of "start-remembering" "stop-remembering", and "do-it" commands enable a text editor to store macros of editing sequences (Gosling, 1981). Except for these special commands, the macro sequence is completely specified by normal editing operations. With a little more effort, such sequences can be named and filed for later use. A practical difficulty with having a special mode — remembering mode — for recording a sequence is that one has frequently already started the sequence before deciding to record it, and so must retrace one's steps and begin again.

The ability to generalize these simple macros could extend their power enormously. Some programming by example strategies allow inclusion of standard programming concepts — variables, conditionals, iteration, and so on — either by inferences from a number of sample sequences, or through explicit elaboration of an example by the user. To illustrate the latter, an experimental system has been constructed for the Xerox Star office workstation which operates according to the direct manipulation paradigm (Halbert, 1981 and 1984). In earlier versions of this system, a pop-up menu allowed one to indicate explicitly the generalization required. For example, icons selected at specification time are disambiguated by name, position, or by asking for a similar object. But because people found it hard to elaborate programming constructs when tracing through an example, later versions have users specifying constructs after macro composition through an editor (Halbert, 1984).

Concluding Remarks

Three classes of reuse facility were distinguished in this chapter: history mechanisms; adaptive systems; and programming by example. A large number of *ad hoc* implemented designs were surveyed within this framework, illustrating the diversity of techniques available. Some methods are less than promising because the cognitive and mechanical effort required to reuse most old submissions is obviously greater than entering them anew.

The taxonomy of reuse facilities presented in this chapter is oriented toward a survey of designs, and is certainly not the only structure possible. Distinctions of reuse facilities could follow user-centered system design, an approach generally advocated by Norman and Draper (1986). For example, Lee (1988b) gives the following eight ways that people could make use of a history facility[3].

- *History for reuse* allows a person to reuse an old item.
- *Relating input and output* is a more specialized form of reuse, for it further describes and disambiguates the objects and actions of reference in the context of the dialog.
- *History through navigation* allows users to reflect on where they have been and where they are now, and use it to guide their progress.
- *History through user recovery* includes undo capabilities.
- *History for functional grouping* lets users group a set of history items into a functional unit.
- *Recording and playback* covers verbatim replay of action sequences.
- *History for consultations and reminders* allows the user to consult past actions and provides him with reminders.
- *History for prediction* helps anticipate and predict what the next user com-

[3]Lee's distinctions incorporate and cite the ones made in this chapter.

mand would be.

A key deficiency in both surveys (and in this general area) is the dearth of empirical evidence justifying chosen designs for reuse facilities, either *a priori* through knowledge of how people repeat activities, or *post hoc* by evaluating their actual use. Nor is there any feeling of how intuitive and empirical knowledge gleaned from one application would generalize to others. The next three chapters address these deficiencies.

Chapter 5

Recurrent Systems

Schemes for activity reuse are based upon the assumption that the human-computer dialog has many recurring activities. Yet there is almost no empirical evidence confirming the existence of these recurrences or suggestions of how observed patterns of recurrences in one dialog would generalize to other dialogs. The next few chapters address this dearth. They provide empirical evidence that people not only repeat their activities, but that they do so in quite regular ways[1]. This chapter starts with the general notion of *recurrent systems*, where most users predominantly repeat their previous activities. Such systems suggest potential for activity reuse because there is opportunity to give preferential treatment to the large number of repeated actions. A few suspected recurrent systems from both non-computer and computer domains are examined in this context to help pinpoint salient features. Particular attention is paid to repetition of activities in telephone use, information retrieval in technical manuals, and command lines in UNIX. The following chapters further examine UNIX as a recurrent system, and then generalize the results obtained into a set of design properties.

[1]Some of the findings in this chapter were first presented at the 1988 ACM CHI Conference on Human Factors in Computing Systems held at Washington D.C. (Greenberg and Witten, 1988a).

5.1 A definition of recurrent systems

An *activity* is loosely defined as the formulation and execution of one or more actions whose result is expected to gratify the user's immediate intention. It is the unit entered to incremental interaction systems (as defined in Section 1.2.1) (Thimbleby, in press). Entering command lines, querying databases, and locating and selecting items in a menu hierarchy are some examples. Copy typing is not. It is continuous rather than incremental, and it is not a cognitive activity (at least, not for the skilled typist).

A *recurrent system* is defined as an open-ended system in which users predominantly repeat activities they have invoked previously[2]. In other words, although many activities are possible, most (but not all) are repetitions of previous ones rather than being freshly generated.

The fundamental notion behind recurrent systems is that activities are repeated. The frequency of repeats is called the *recurrence rate*, and it identifies the probability that any activity is a repeat of a previous one. The *total activities* is a count of all submissions the user has entered, while *different activities* count only those that are different. The recurrence rate $\mathcal{R}$ over a set of user activities is calculated as:

$$\mathcal{R} = \frac{total\ activities - different\ activities}{total\ activities} \times 100\%$$

For a system to be classed as "recurrent", the recurrence rate may exhibit a moderate variation across users, provided that the average rate is fairly high.

Although many old activities are repeated, new ones are constantly added to the repertory. The rate at which new activities are composed and introduced to the

[2]I first conceived the idea of recurrent systems in an earlier work (Greenberg, 1984). Originally called *repetitively accessed data bases*, it concerned information retrieval of items from a data base. The current term and definition subsumes the previous one.

dialog is the ***composition rate*** $\mathcal{C}$:

$$\mathcal{C} = \frac{different\ activities}{total\ activities} \times 100\% = 100 - \mathcal{R}$$

Activity formation within recurrent systems is open-ended, as there are a very large number of possible activities available. A *dynamic* recurrent system is one that incorporates new activities regularly. They are *static* when $\mathcal{C}$ is close to zero (*eg* using commands, Chapter 3). Even when new activities are constantly generated, only a small subset of the possibilities could be selected by any one user.

One purpose of this chapter is to clarify further what a recurrent system is. A few systems that fit the definition above are studied and their common properties extracted. To start with, command use is obviously a recurrent system. It seems reasonable to suggest that the findings reported in Chapter 3 are also properties of recurrent systems. First, the set of activities invoked by any particular user is typically a small subset of the activities usually available. Second, the set of activities invoked may be disjoint or overlapping for different users of the system. Finally, different people may repeat common activities at different rates, and particular activities may be repeated by the same user at very different rates. The frequency distribution of activity selection is not expected to be uniform.

This definition and list of properties is not a strong one, for the boundary between recurrent and non-recurrent systems is not distinguished. Such a boundary specification, even a "fuzzy" one, would be subjective and would also depend upon other aspects of the system being investigated. For example, time between recurrences might be a consideration, where only short-term recurrences are counted but those repeated only after long intervals are considered different. Still, the properties provide a reasonable checklist for judging whether particular systems have potential for reuse.

It would seem that, at least on the surface, recurrent systems are just a weaker way of denoting patterns of behaviour already well described by Zipf's law. However, major differences exist. First, many human-oriented observations characterised by Zipf's law are based upon cumulative results of the population. One study, for example, examined the statistics of all terms used to retrieve items over all users of two separate bibliographic data bases, and describes how they conform to Zipf's law (Bennett, 1975). Similar large-scale statistics have been applied to many facets of library science (a list is given by Peachey, Bunt and Colbourn, 1982). Yet there is no evidence that the same distribution applies to individuals. Recurrent systems, on the other hand, are centered around the statistics of activities of individuals, rather than large groups. Second, Zipf's law typically deals with very large numbers, and tends to break down with few observations (see Bennett, 1975 for one example). Recurrent systems are quite comfortable with small numbers. As will be seen, patterns within some recurrent system may be identified by observing a sequence of less than 100 actions performed by one individual→ §5.2.1.

5.2 Recurrent systems in the non-computer world

Are recurrent systems just artifacts peculiar to computer use, or are they every day phenomena in the natural world? This section suggests the latter. Without belaboring the point, a few natural and reasonable possibilities follow.

- A cookbook has a subset of recipes referred to repeatedly by a single homemaker. However, usage patterns differ as not all people favor the same recipes. Some cooks prefer tried and true recipes, and will thus use a small set of recipes many times. Others desire variety and select from a larger recipe set with less repetition. A similar analogy may be made to selections from a book of verse, readings in the bible, or sections and columnists read in a newspaper.
- An audiophile listens to different records repeatedly. Some are heard more than others, and new styles come into favor while old ones fall out.

- Within tool-oriented contexts, tradespeople and artisans use some tools more often than others.
- Procedures carried out by most office workers are routine. Still, special procedures are sometimes followed for rarer conditions and exceptions, while new ones are created to handle unexpected situations.

Empirical evidence supports the existence of recurrent systems in a variety of task domains. Telephone use is one example, and our investigation is described in this section. Subsequent sections will illustrate two other examples: retrieving topics from technical manuals, and entering command lines in UNIX.

5.2.1 Telephone usage — a limited study

Telephone usage is examined as a first example of a recurrent system, where an activity is simply a number being dialed. This seems a natural choice, for we know from experience that:

- many calls are to people/firms that have been called before;
- some calls are new ones not made before;
- numbers are called with differing frequencies;
- usage patterns evolve slowly over time.

This section will describe a few simple analyses that determine empirically some characteristics of telephone usage as a recurrent system.

A small-scale study was conducted previously on individual telephone usage, as reported in an earlier work (Greenberg, 1984). The intent was to inspect telephone usage for patterns of recurrences in the numbers dialed. Fourteen telephone users known to the researcher were asked to keep a list of all calls originating from their

Measures	Results per subject				
	1	2	3	4	5
Total Calls	313	129	119	106	106
Different Calls	104	55	60	53	39
Recurrence Rate	66.8%	57.4%	49.6%	50%	63.2%
Average Recurrence Rate	57.4% (*std dev* = 7.7)				

Table 5.1: Telephone usage statistics

office and/or home telephones. Instructions were to record consistently all completed calls they had made, including busy or wrong numbers and repeated calls. The time frame varied from one to three months. Although the original report summarized results for all subjects, the present analysis removes artifacts due to subjects who had made relatively few calls. Only those five users who had made over one hundred calls are described here. Data is also re-analyzed to see how new calls are generated over time, to review the equilibrium of the apparently stable recurrence rate, and to see if the frequency distribution of recurring numbers exhibits temporal recency.

Telephone use by the top five single users was surveyed and compiled, with the results summarized in Table 5.1. The collected data was surprisingly consistent in many respects. First, new telephone numbers were dialed regularly, as indicated by the relatively smooth and seemingly linear lines in Figure 5.1. The horizontal axis represents the number of calls made, while the vertical axis indicates the number of different calls. This result suggests that telephone use is not restricted to a few numbers dialed repeatedly, but is, in fact, open-ended.

How many calls are recurrences of previous ones? The recurrence rate $\mathcal{R}$ calculated over all calls made by each subject is noted in Table 5.1. The average observed value over all users is about 57%.

But how stable is the recurrence rate (or, for that matter, the seemingly linear

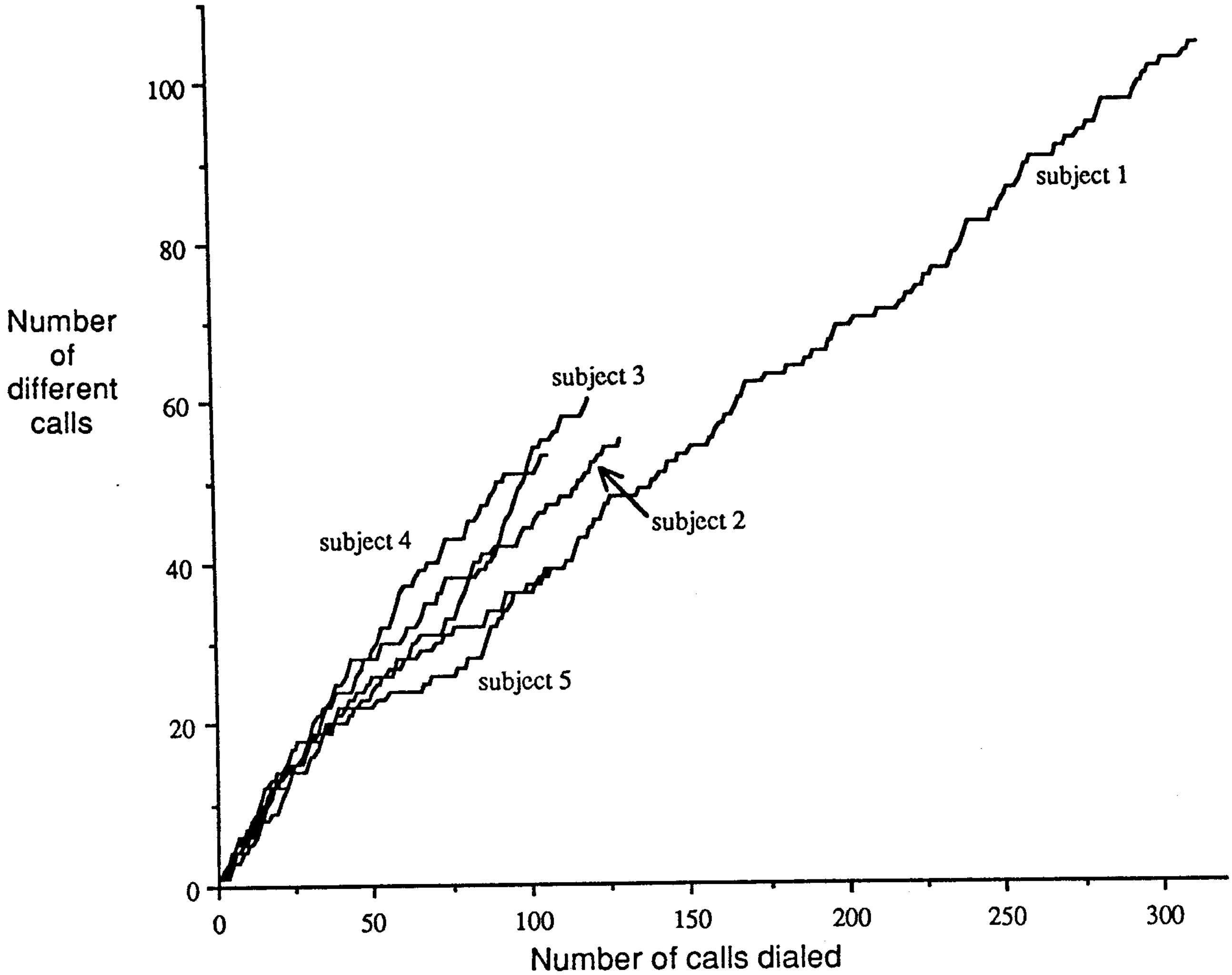


Figure 5.1: The number of different calls made versus the number of calls dialed so far

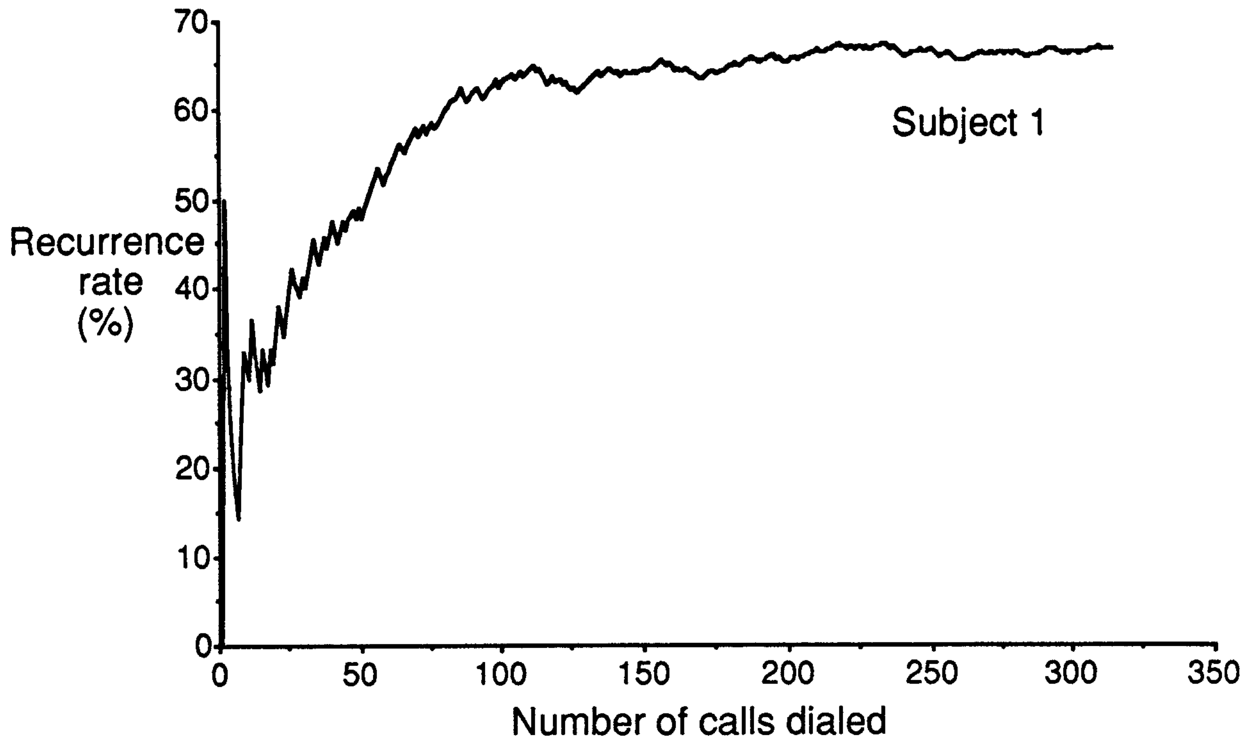


Figure 5.2: Relation between recurrence rate and the number of calls made

composition rate)? What is the relationship between the rate and the number of phone calls dialed by a single user? The recurrence rate over the number of calls made was re-analyzed, and the result for the most prolific caller (subject 1) is plotted in Figure 5.2[3]. The graph indicates that the rate of recurrences rises quickly over the first twenty calls and less quickly up to one hundred calls. The original report noted that $\mathcal{R}$ then seems to approach an equilibrium. However, a regression analysis made on the recurrence rate for 150 calls and over indicates a positive correlation between the rate and the number of calls dialed ($r = .661, df = 162, p << .01$), although the rate of increase is small ($slope = .012$). As the recurrence rate $\mathcal{R}$ should equal the slope of Figure 5.1 (the composition rate $\mathcal{C}$), the trends seen there

[3]While the original graph in Greenberg (1984) averaged the data points over slices of ten calls, Figure 5.2 gives a true mapping of the recurrence rate up to each call. Also, only one subject is drawn here for clarity. Plots of the other subjects showed similar trends.

are, in fact, non-linear.

Note that the study observed people who already had established patterns of telephone use. The initial recurrence values (and their corresponding inflated composition rate) are low only because some established and highly repeated numbers are being encountered for the first time. One interpretation of the graph is that users repeat phone numbers almost immediately, as shown by the rapid initial rise. Secondly, some calls are probably repeated over a slightly longer period of time, as revealed by the slow but steady increase in the middle of the curve. Finally, there is a near cessation of increase in the rate of recurrences after eighty calls. This indicates that although some calls are repeated over a long time period, a high number of new and rarely repeated calls are made. For example, the composition rate C was estimated at 33% for this subject (as shown in Figure 5.1). There seems to be four general categories of calls: highly popular numbers which are called quite often; moderately popular ones called infrequently; once-only calls which are never or very rarely repeated, and new ones never seen before that are incorporated in the repertory. This view agrees well with introspective expectations.

The original report also examined the frequency distribution of all calls made, by ranking each subject's calls by frequency. Of particular importance in the findings is the decreasing trend in frequency of use over the calls, indicating a diverse spectrum between highly and rarely repeated numbers. It was suggested that the same decreasing trend can be loosely modeled by the Zipf distribution, although the Zipf decrease is significantly more pronounced than in the telephone usage distribution.

Finally, telephone numbers that have just been dialed are more likely to be repeated than those dialed long ago. This notion of "temporal recency" is illustrated by the five frequency distributions, one for each subject, drawn in Figure 5.3. The method of analysis is described in Section 5.4.2. The horizontal axis represents the distance of the number about to be submitted from the position of a matching old

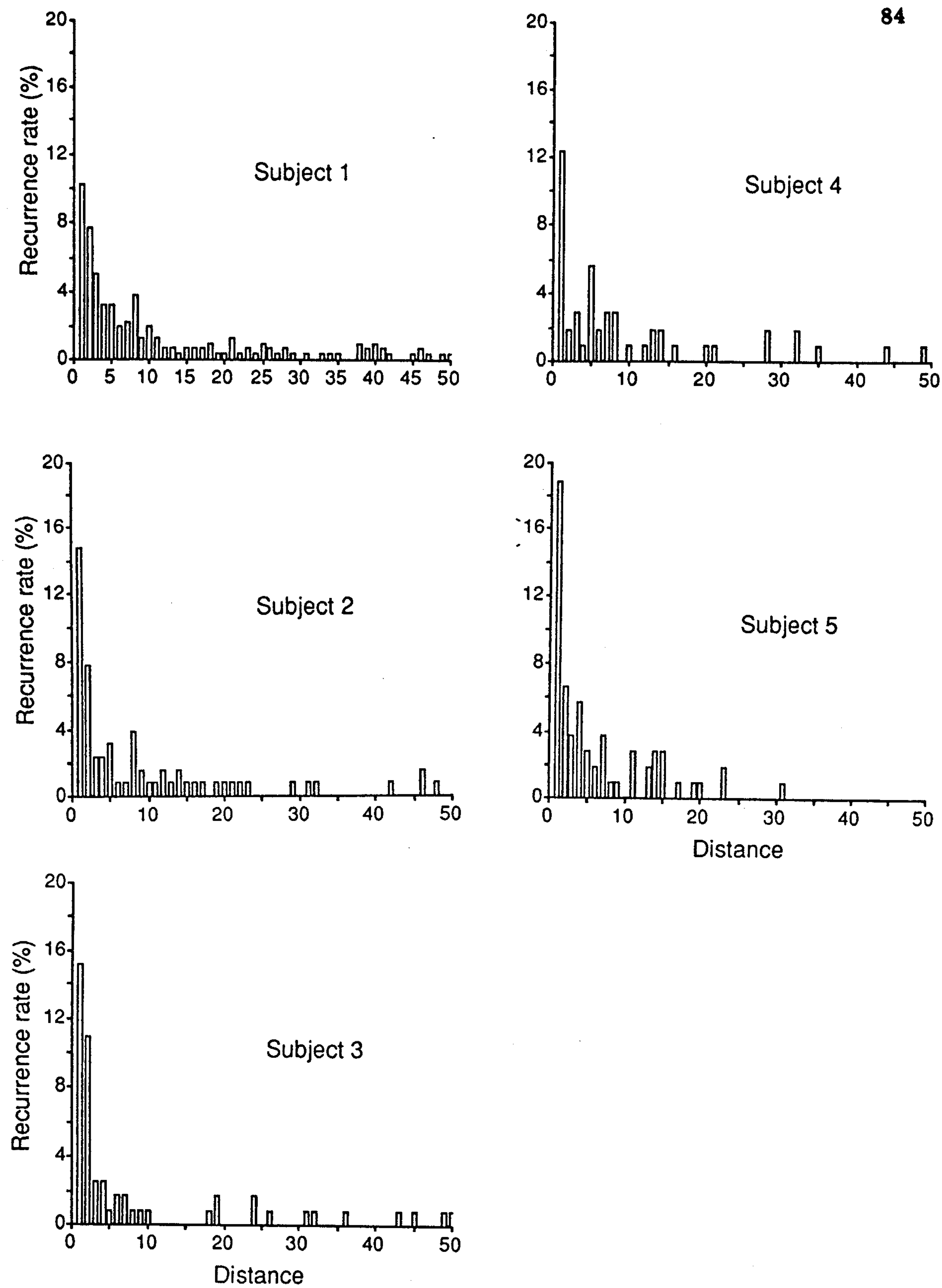


Figure 5.3: Recurrences of phone numbers as a measure of distance

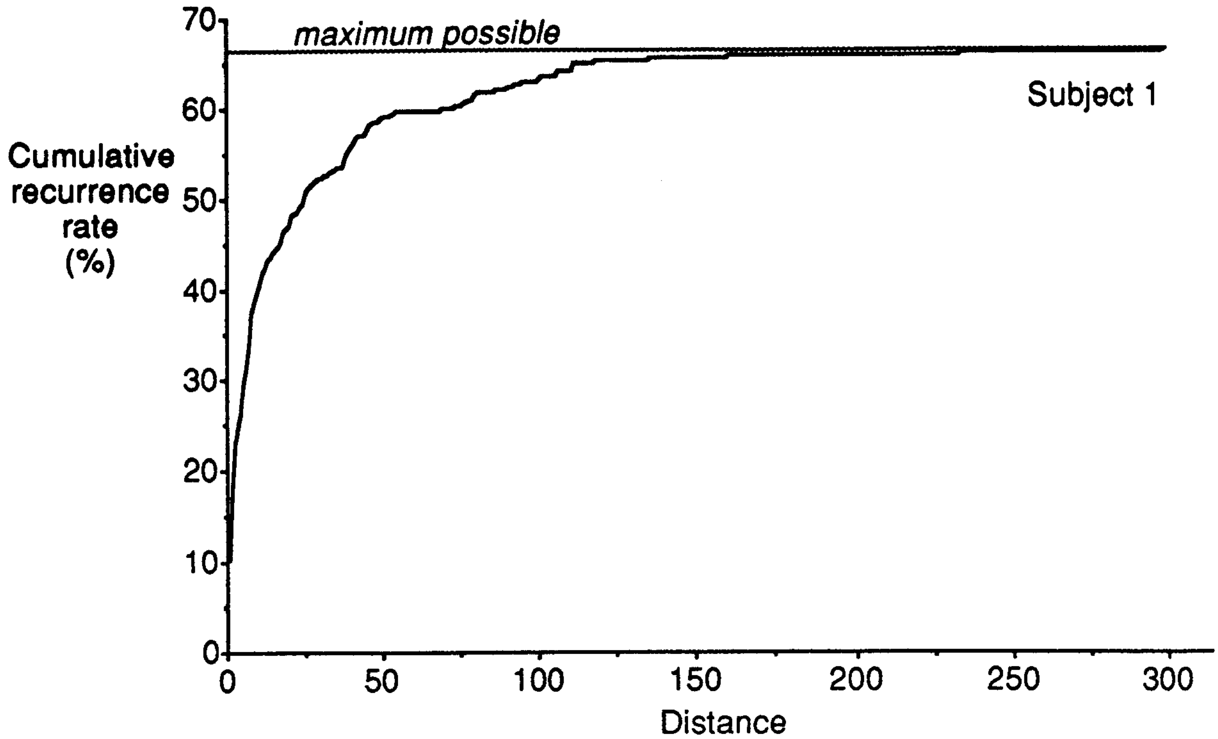


Figure 5.4: Cumulative recurrences of phone numbers as a measure of distance

one maintained in a temporally-ordered list. The vertical axis shows the recurrence rate for particular distances. For example, 10% of Subject 1's calls are a repeat of the last call made, 8% repeat the second from last, 5% the third from last, and so on down the list. Figure 5.4 draws the same results for Subject 1 in a slightly different way — the vertical axis is now the running sum of recurrences over distance. For example, around 41% of all calls are repeats of one of the previous 10 dialed. The horizontal line at the top is $\mathcal{R}$ (67%) which, since new calls are also composed regularly, is the limit of the running sum. The striking feature of both figures is that the last few calls are more likely to be repeated than any others[4].

In summary, the review of this study indicates that telephone usage is a dynamic

[4]Even if this distribution were uniform, the last few calls would still exhibit a higher frequency of recurrence, and could be misconstrued as temporal recency. Still, the recency effect is more pronounced in these figures and the artifacts of uniform probability are ignored. Appendix 4 describes the uniform probability distribution, explains why this distortion occurs, and details why the effects were ignored.

recurrent system, and adds the property that the probability of an item recurring is related to its recency of selection. However, the limited number of subjects polled over a relatively short time period does not supply enough data to support anything but general statements about usage patterns.

5.3 Recurrent systems in information retrieval

A second potential area of high recurrences is in information retrieval. Intuitions about the recurrence rate of such systems are perhaps not so immediate as with telephone access. Still, a few arguments for suspecting recurrences follow. First, it is usually difficult to remember particular details of information retrieved, especially if it is obscure, technical or numerical in nature. Retrieval recurrences over short time periods is therefore likely, since details of a document require constant reviewing. Second, different information fragments are not sought equally. People may recall "important" information fragments repeatedly over long time periods. Finally, previously acquired information may become stale. As information is rarely static, the same question may be posed repeatedly and the answer checked for changes. Airline arrival and departure information available through teletext environments is one example of dynamic information. Another example is the slowly changing standards described in technical manuals, which become obsolete over time.

This section reviews how people retrieve topics in one type of information system — technical manuals.

5.3.1 Retrieving topics in manuals

Empirical evidence supports the existence of manuals as recurrent systems. M.E. Lesk, in an analysis of work logs of Boeing engineers, noted that up to 70% of all lookups of hardcopy manuals (*eg* standards, product manuals) were to specific things the engineers had seen before but had forgotten (reported in Dumais and Landauer, 1982). The high figure is perhaps not surprising in retrospect, for technical details found in engineering manuals do not lend themselves to easy recall.

A previous study shows that topic retrieval in computer-based technical manuals is also characterised by high recurrences. All usages of the UNIX on-line manual by students and employees in a Computer Science department were collected for one month (Bramwell, 1983) and analyzed for recurrences (Greenberg, 1984). A total of 4978 correct retrievals was made by 443 users. The salient findings are summarized here.

1. The recurrence rate of retrievals was generally high, approaching an average of 50% for each user after relatively few retrievals.
2. Moderate variation in the recurrence rate was noted between individuals. For example, users who had made between 17 – 19 retrievals had a standard deviation of 17.1% over the average rate of 45.2%. Extremes were 12% and 71%.
3. Each user retrieved only a small subset of the topics available.
4. Few common retrievals were noted between users, even when user tasks were similar.
5. The frequency distribution of the topics retrieved by an individual varied substantially from user to user. Although no uniform distribution was noted, the general trend was to access most topics between one and three times, with a smaller set being called on more often.

In general, one can conclude that retrieving topics in technical manuals is highly repetitive. The properties of recurrent systems listed so far are also supported. It is hypothesised that these results generalize to most structured documents, such as those found in hypertext systems, and to general information retrieval facilities provided by standard data bases. Further work is required to substantiate this hypothesis.

5.4 Unix csh as a recurrent system

As mentioned previously, command use is certainly a recurrent system, although it is a "static" one since C is so low. A separate question is whether complete command lines submitted to general-purpose command-based environments also follow the properties of recurrent systems. If they do, what patterns do these recurrences exhibit? This section investigates statistics of command line recurrences by subjects using the UNIX *csh*.

As commands often act on objects and are qualified with options, it is important to look at the command line as a whole (see the concluding remarks of Chapter 3). After introducing some terminology, two questions particularly relevant to reuse facilities are addressed in this section. They both concern the statistics of complete command lines entered by the user to UNIX. This is particularly important, for lines are the incremental unit of *csh*. Also, reuse facilities usually simplify redoing the complete activity, rather than its isolated components. The section first examines how often a user actually repeats command lines over the course of a dialog. Particular attention is paid to the variation in this rate between groups and between individuals, and its stability over the number of command lines entered. Second, the probability that the next command line will match a user's previous input is described. This is measured as a function of the number of entries that have elapsed since that input.

In the following discussion, a *command line* is a single complete line (up to a terminating carriage return) entered by the user. This is a natural unit because commands are only interpreted by the system when the return key is typed, and the complete line is a more detailed reflection of one's activity than just the command itself. Command lines typically comprise an action (the command), an object (*eg* files, strings) and modifiers (options). A sequential record of command lines entered by a user over time, ignoring boundaries between login sessions, is known as a *history list*. Erroneous submissions noticed by *csh* are not included. Unless stated otherwise, the history list is a true sequential record of every single command line typed. Duplicate activities, for example, are included. The *distance* between two lines is the difference between their positions on the list. A *working set* is a small subset of items on the history list. The number of different entries in the history list is the command line *vocabulary*. Although white space is ignored, syntactically different but semantically identical command lines are considered distinct[5].

5.4.1 Recurrences of command lines

Although, as Section 3.3 showed, only a few commands account for all actions of a particular user, it is not known how often new command lines are formed and old ones recur. This is important, as it is the recurrence rate — the probability that the next item has been previously entered — that existing reuse facilities exploit best. One might expect that command lines would recur infrequently, given the limitless possibilities and combinations of commands, modifiers, and arguments. Surprisingly, this is not the case.

I investigated how often lines are repeated by counting the command line vocabulary size. Let $t_{cmd\ lines}$ be the total number of command lines entered by the user (*ie* the size of the history list), and $v_{cmd\ lines}$ be the vocabulary size, or number of distinct items in that set. The overall recurrence rate, using this slightly different terminology, is calculated as described in Section 5.1:

$$\mathcal{R} = \frac{t_{cmd\ lines} - v_{cmd\ lines}}{t_{cmd\ lines}} \times 100\%$$

[5]For example, the command lines "ls -las" and "ls -lsa" are treated as different vocabulary items, even though they mean the same thing. Although this strategy overestimates the vocabulary size, a semantic analysis was deemed too expensive for the large data set covered.

Do users extend their vocabularies continuously and uniformly over the duration of an interaction? If not, then the recurrence rate, measured locally, will change over time as the user's history list grows. Furthermore, calculating group means for $\mathcal{R}$ could be confounded by the large variation between the number of command lines each user enters, which was noted in Table 2.1. As $\mathcal{R}$ is a function of $v_{cmd\ lines}$ and $t_{cmd\ lines}$, it is necessary to investigate how the vocabulary size depends upon the actual number of commands entered. If users never extend their vocabulary after some short initialization period, little correlation with $t_{cmd\ lines}$ is expected. On the other hand, a strong correlation is likely if new command lines are composed regularly by a user.

A simple regression analysis was performed by contrasting $t_{cmd\ lines}$ and $v_{cmd\ lines}$ for each subject. The regression line is plotted in Figure 5.5a, where each point in the scattergram represents the value observed for each subject at the end of the study period. A statistically significant and strong correlation was found ($r = .918$, $df = 167$, $p < .01$). The moderate slope ($C = 23\%$) of the regression line makes the correlation practically significant as well.

It seems reasonable from the scattergram of Figure 5.5a that $v_{cmd\ lines}$ increases linearly with $t_{cmd\ lines}$, indicating that the recurrence rate is independent of the actual number of lines entered. This was checked in two ways. The first was a simple regression analysis of $t_{cmd\ lines}$ with $\mathcal{R}$. The regression line is shown in Figure 5.5b. Here, each point represents the recurrence rate observed for each subject at the end of the study. A statistically significant correlation was found ($r = .253$, $df = 167$, $p < .01$), indicating that the recurrence rate increases with the number of commands entered. However, the high variance of data points around the line ($r^2 = .064$), and its low slope (0.002), makes this finding insignificant for practical purposes. Consequently, $\mathcal{R}$ is considered independent of $t_{cmd\ lines}$.

The second and perhaps more convincing way of observing the independence of the recurrence rate is by examining in detail the vocabulary growth of individuals.

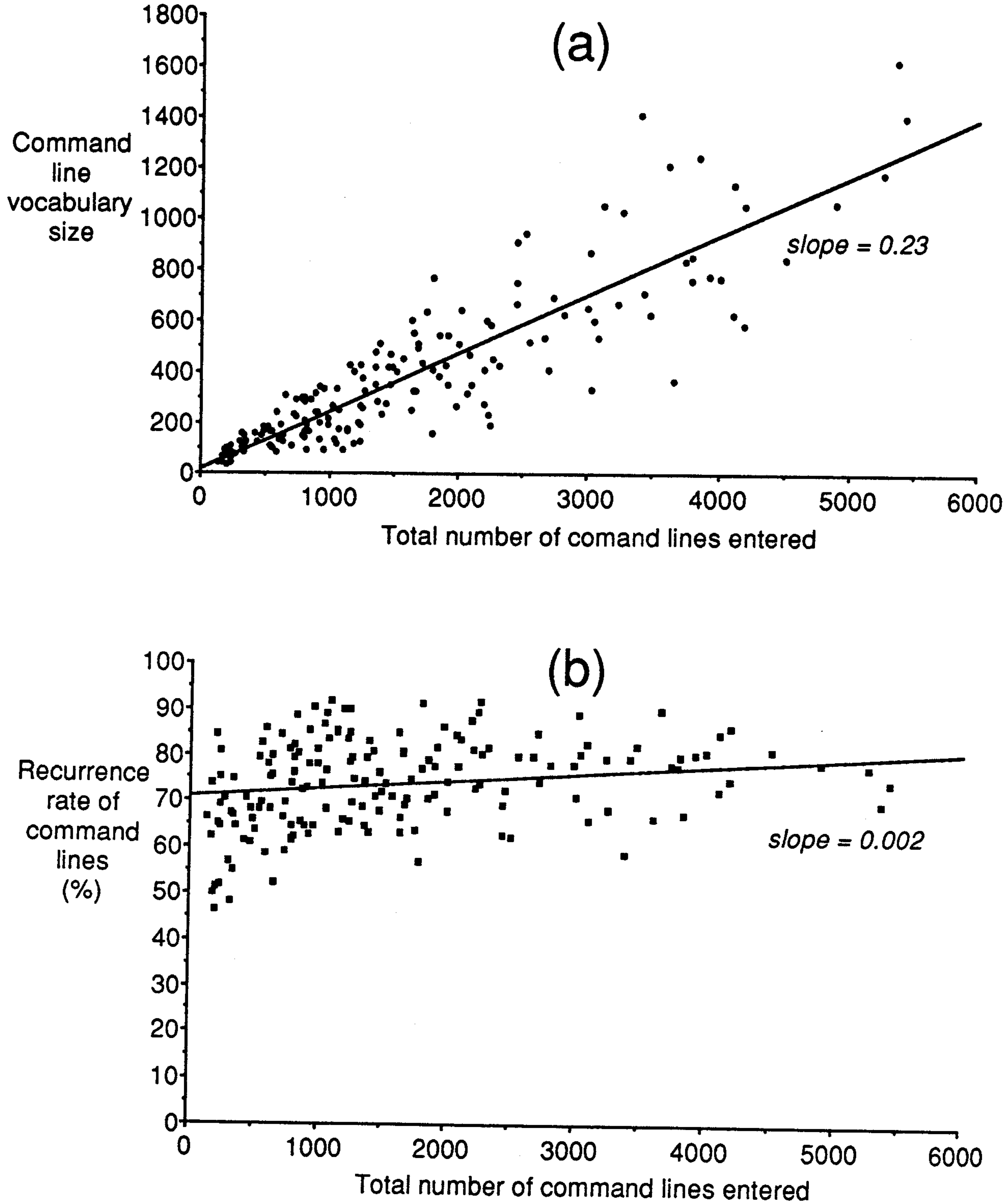


Figure 5.5: Regression: a)Command line vocabulary size; and b) the % recurrence rate versus the total commands lines entered by each subject

Sample Name	Recurrence Rate		Range	
	mean	std dev	minimum	maximum
Novice Programmers	80.4%	7.2	64.7%	91.7%
Experienced Programmers	74.4%	9.7	51.4%	90.0%
Computer Scientists	67.7%	8.2	46.4%	82.0%
Non-Programmers	69.4%	8.1	50%	84.3%
Total	73.8%	9.6	46.4%	91.7%

Table 5.2: The average recurrence rate of the four sample Unix user groups

The formation of new command lines is surprisingly linear and regular, as illustrated by Figure 5.6. Similar to Figure 3.2, and using the same typical users, the horizontal axis still represents the number of lines entered so far, but now the vertical axis indicates the size of the command line vocabulary. For example, the scientist subject has composed close to 1400 new command lines after 6000 lines were entered. The long periods of quiescence and the flurries of new activity seen in Figure 3.2 are notably absent from Figure 5.6.

Table 5.2 lists the mean recurrence rate, standard deviation, and ranges of $\mathcal{R}$ for each subject group. An analysis of variance of raw scores rejects the null hypothesis that these means are equal ($F(3,164) = 21.42, p < .01$). The Fisher PLSD multiple comparison tests suggests that all differences between group means are significant ($p < .01$), excepting the Non-programmers versus Scientists. As the Table indicates, the mean recurrence rate for groups ranges between 68% and 80%, with Novice Programmers exhibiting the highest scores.

Although recurrence rate depends upon user category, and very slightly on the number of command lines entered, it is reasonable to simplify this descriptive statistic by assuming the mean $\mathcal{R}$ over all users to be 75% and $\mathcal{C}$ of 25%, independent of $t_{cmd\ lines}$. In other words, an average of three out of every four command lines entered by the user already exist on the history list. Conversely, an average of one out of every four command lines appears for the first time.

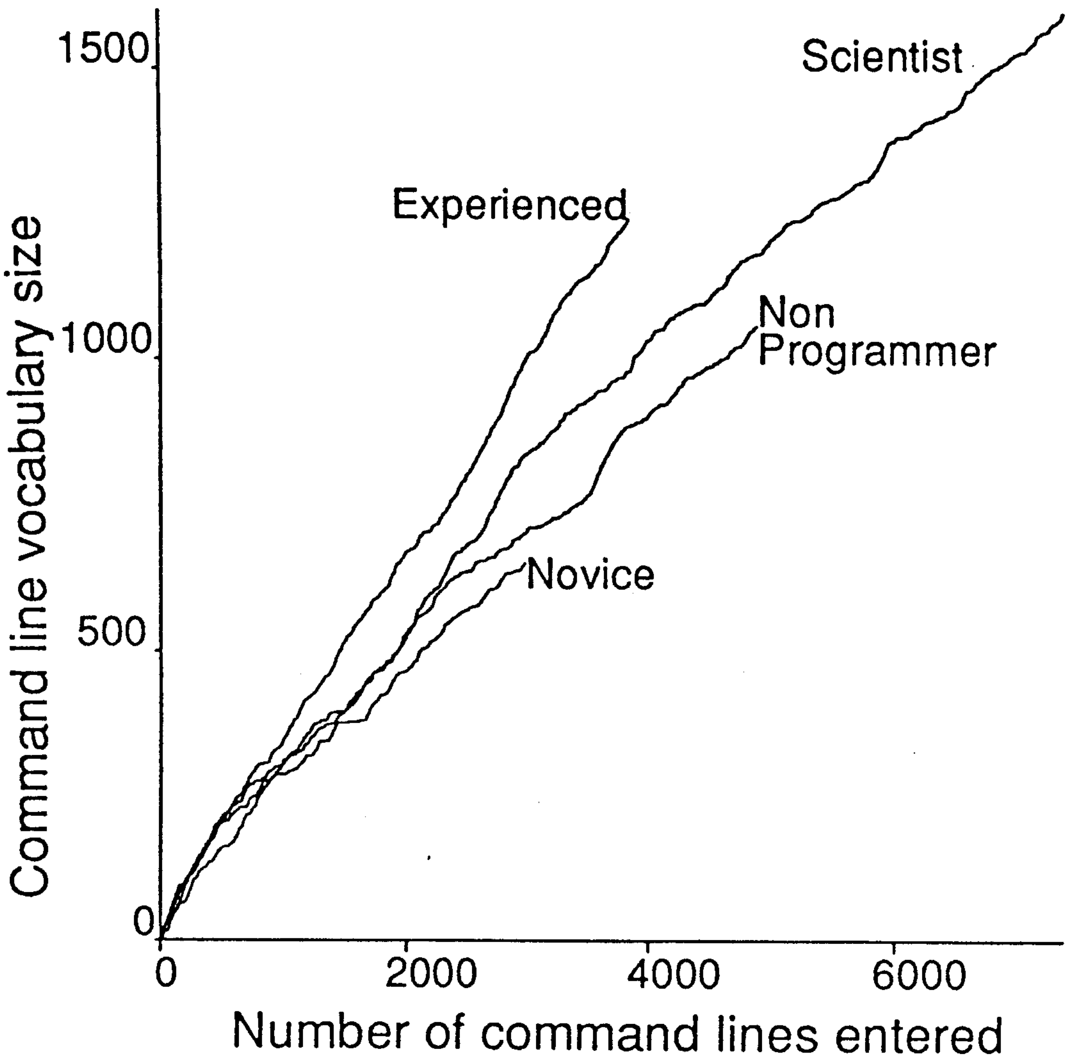


Figure 5.6: Command line vocabulary size versus the number of commands entered for four typical individuals

5.4.2 Command-line frequency as a function of distance

For any command line entered by a user, the probability that it has been entered previously is quite high. But how do previous items contribute to this probability? Do all items on the history list have a uniform probability of recurring, or do the most recently entered submissions skew the distribution? If a graphical history mechanism displayed the previous p entries as a list (*eg* HISTMENU, Bobrow 1986), what is the probability that this includes the next entry?

The recurrence distribution as a measure of distance was calculated for each user. First, let $\mathcal{R}_{s,d}$ be the recurrence rate at a given distance for a single person, obtained by processing each subject's data. Figure 5.7 shows the algorithm used to obtain all values of $\mathcal{R}_{s,d}$ from a subject's trace. The mean recurrence rate for a given distance d over all S subjects in a particular group is then calculated as:

$$\mathcal{R}_d = \frac{1}{S}\sum_{s=1}^{S} \mathcal{R}_{s,d}$$

These group means are plotted in Figure 5.8a. The vertical axis represents $\mathcal{R}_d$, the rate of command line recurrences, while the horizontal axis shows the position of the repeated command line on the history list relative to the current one. The slight distortional effects of the uniform probability distribution are ignored (see Appendix 4). Taking Novice Programmers, for example, there is a $\mathcal{R}_{d1} = 11\%$ probability that the current command line is a repeat of the previous entry (distance = 1), $\mathcal{R}_{d2} = 28\%$ for a distance of two, $\mathcal{R}_{d3} = 9\%$ for three, and so on. The most striking feature of the Figure is the extreme recency of the distribution.

The previous seven or so inputs contribute the majority of recurrences. Surprisingly, it is not the last but the second to last command line that dominates the distribution. The first and third are roughly the same, while the fourth through seventh give small but significant contributions. Although the probability values of $\mathcal{R}_d$ continually decrease after the second item, the rate of decrease and the low values make all distances beyond the previous ten items equivalent for practical pur-

Given:

- a trace numbered from 1 through n, where n is the last line entered;
- an array of counters used to accumulate the number of recurrences at a particular distance.

Algorithm:

```
/* For each item, find its nearest match on the history list */
/* and record it */
for (i := 1 to n)
      for (j := i-1 downto 1)
            if (submission_i = submission_j) then begin
                  distance := i-j;
                  counter[distance] := counter[distance] + 1;
                  break; /* jump out of inner loop */
            end
/* The averaged value found in each counter is R_s,d */
for (distance := 1 to n)
      counter[distance] := (counter[distance]/n) * 100;
```

Figure 5.7: Processing a subject's trace for all values of $\mathcal{R}_{s,d}$

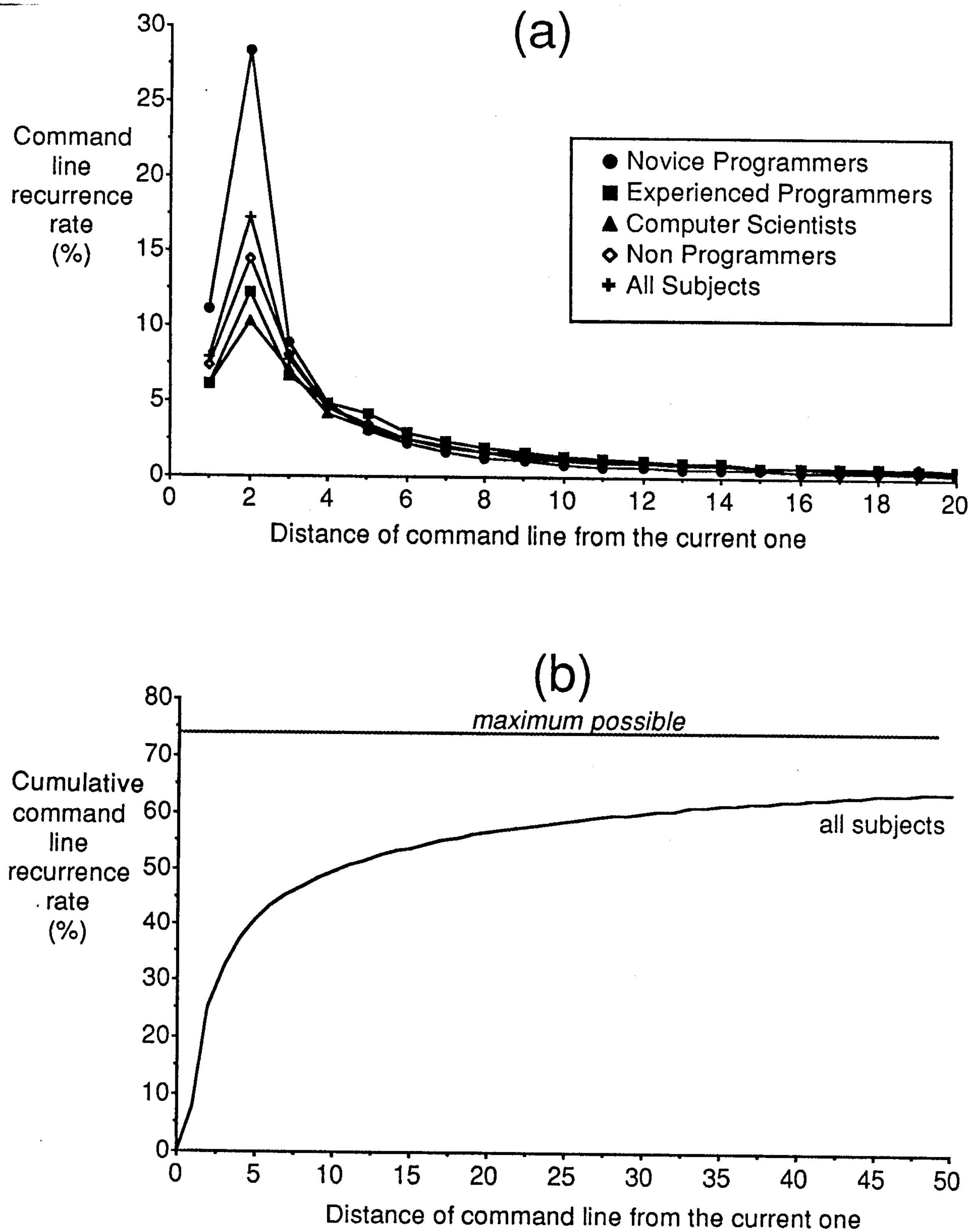


Figure 5.8: a) Recurrence distribution; and b) cumulative recurrence distribution as a measure of distance

poses. This is illustrated further in Figure 5.8b, which plots the same data for the grouped total as a running sum of the probability over a wider range of distances. The running sum of the recurrence rate up to a given distance D for a single person is called $\mathcal{R}_D$. Its mean value over a group of subjects is calculated as

$$\mathcal{R}_D = \frac{1}{S}\sum_{s=1}^{S}\sum_{d=1}^{D}\mathcal{R}_{s,d}$$

The most recently entered command lines on the history list are responsible for most of the cumulative probabilities. For example, there is a $\mathcal{R}_{D_{10}} = 47\%$ chance that the next submission will match a member of a working set containing the ten previous submissions. In comparison, all further contributions are slight (although their sum total is not). The horizontal line at the top represents a ceiling to the recurrence rate, as $\mathcal{C} = 26\%$ of all command lines entered are first occurrences.

Figure 5.8a also shows that the differing recurrence rate between user groups, noted previously in Table 5.2, are mostly attributed to the three previous command lines. Recurrence rates are practically identical elsewhere in the distribution. This difference is strongest on the second to last input, the probability ranging from a low of 10% for Scientists to a high of 28% for Novice Programmers.

Concluding Remarks

This chapter introduced the notion of recurrent systems and provided empirical evidence of their existence in both natural and computer domains. The three diverse examples studied — telephone usage, information retrieval, and command-line interfaces — show remarkable similarity in the way activities are repeated. All satisfy the (admittedly vague) definition of recurrent systems set out in Section 5.1. A few common properties of recurrent systems were also stated.

The statistics of UNIX *csh* use, and to lesser extent telephone dialing, indicate that the most recently submitted activities are the most likely to be repeated.

These statistics confirm the potential of reuse facilities in general, and verify the assumptions of recency made by history mechanisms.

Four major weaknesses and criticisms of the idea of recurrent systems and the empirical studies reported in this chapter are noted below. First, the definition of recurrent systems is not precise, as no benchmark values are indicated. This is intentional, as any values provided would be *ad hoc* (although observed values for $\mathcal{R}$ seem to range from 40 – 80%).

Second, the study of telephone usage is very limited. More subjects are necessary and a longer observation period is required, especially considering the initial instability of $\mathcal{R}$ over the first 100 calls. A more rigorous method for recording calls is required as well. Although subjects say they were diligent in recording all calls, there was no way to ascertain that they actually did. Also, other factors should be included in the analysis. For example, what is the effect on the patterns of calls made by teenagers versus adults? What about business versus personal calls?

Third, the study of manual usage is very limited. Although many subjects were available, the relatively small values and the high variance in topic retrievals by subjects makes it difficult to determine statistically significant patterns.

Fourth, undue attention may be paid to recency. Are there better methods for predicting a user's next activity? The next chapter tackles this question.

Finally, traces of subject's activities in all three studies were not annotated. Why do people actually repeat activities? Although this chapter observed that they do, we can only make educated guesses as to the reasons behind their actions.

Chapter 6

Reuse Opportunities in Unix Csh — Potential and Actual

In this chapter, I consider the potential and actual reuse opportunities within UNIX. First, several methods are suggested that could increase the likelihood that the next submission matches an item in a small set of predictions offered to the user for review and reuse. Each method is applied to the UNIX traces, and their predictive "quality" is measured and contrasted against each other. In the second part of the chapter, I investigate how well the reuse facilities supplied by the UNIX shell are used in practice.

6.1 Conditioning the distribution

In the last chapter, particular attention was paid to the recurrence of command lines during *csh* use, and to the probability distribution of the next line given a sequential history list of previous ones. We saw that the most striking feature of the collected statistics is the tremendous potential for a historical reuse facility: the recurrence rate is high and the last few submissions are the likeliest to be repeated.

One may predict what the user will do next by looking at those recent submissions. But there is still room for improvement, since a significant portion of recurrences are *not* recent submissions. Can better predictions of the user's next step be offered? This section proposes and evaluates alternative models of arranging a user's command line history that will condition the distribution in different ways.

The recurrence distributions of Section 5.4.2 were derived by considering all input for a user as one long sequential stream, with no barriers placed between sessions. We have seen that although a small set of recently-entered command lines accounts for a high portion of repetitions, many others lie outside. Consider a working set of the ten previous items on the history list. From Figure 5.8b, there is a $\mathcal{C} = 26\%$ chance that the next command line has not appeared before, a $\mathcal{R}_{D_{10}} = 47\%$ chance that it has occurred within the working set, and a 27% chance that it last appeared further back. This section explores the possibility that the distribution can be conditioned, firstly to increase the recurrence probabilities over a working set of a given size, and secondly to improve the overall "quality" of predictions offered. The following subsections explain how quality is assessed; describe a variety of conditioning techniques; and apply these conditions to the traces that have been collected.

6.1.1 The quality of predictions

Predictions of activities for reuse are only effective when the search for and selection of an offering is less work for the user than submitting it afresh. Work is therefore used to measure prediction quality. The smaller the amount of work required for reuse as opposed to resubmission, the higher the quality of the set of predictions offered. The selection of a high-quality prediction either reduces the cognitive effort of reconstructing the original activity or minimizes the physical work required to enter that activity to the system.

The metric for work introduced here is called M_D, and comprises two components that estimate a prediction's quality. The first is $\mathcal{R}_D$, the probability that the desired item appears on a displayed list of length $p = D$. Its calculation was given in Section 5.4.2. The second, called $\bar{c}_d$, is the average number of characters saved by reusing the matching activities at exactly a particular distance d. Incorporating string length as a partial indicator of work assumes, of course, that longer strings are harder to recall and re-enter than short ones. M_D indicates the average number of characters saved over all submissions when repeated activities are selected from a list of candidates of length D. By using M_D, predictive methods can be numerically compared and ranked accordingly.

The calculation of M_D and its components proceeds as follows. First, let $\bar{c}_{s,d}$ be the average number of characters saved by a subject s per recurrence at distance d, calculated as:

$$\bar{c}_{s,d} = \frac{c_{s,d}}{r_{s,d}}.$$

The term $c_{s,d}$ is the total number of characters saved by the subject reusing all matching recurrences at a particular distance, and $r_{s,d}$ is the number of matching recurrences at that distance. When $\bar{c}_{s,d}$ is averaged over all subjects S, we get $\bar{c}_d$, calculated as:

$$\bar{c}_d = \frac{1}{S}\sum_{s=1}^{S} \bar{c}_{s,d}.$$

But $\bar{c}_d$ just gives the average characters saved by using a correct prediction at a particular distance. An alternative approach calculates M_d, which includes the probability that the prediction is correct. More specifically, M_d is the mean number of characters saved at a particular distance over all subjects:

$$M_d = \frac{1}{S}\sum_{s=1}^{S} \bar{c}_{s,d}\mathcal{R}_{s,d},$$

where $\mathcal{R}_{s,d}$ is a particular subject's probability of a recurrence at the given distance, defined in Section 5.4.2 . Note that M_d differs from $\bar{c}_d$ as it is the average savings *per submission* rather than per recurrence. The final step in calculating M_D shows the cumulative average savings in characters per submission when one through D

predictions are available for selection:

$$M_D = \sum_{d=1}^{D} M_d = M_1 + M_2 + \ldots + M_{d=D}.$$

Both $\mathcal{R}_D$ and M_D will be used in this chapter as metrics for evaluating working sets of particular sizes, although values of $\mathcal{R}_d$ (→ §5.4.2) and $\bar{c}_d$ are included for reference.

6.1.2 Different conditioning methods

A variety of conditioning methods are described here. As well as conditions that are expected to perform quite well, weak ones that have been implemented in existing reuse facilities are also included. For each method I indicate how the recorded data will be analyzed to assess its effectiveness. The algorithms used to find $\mathcal{R}_{s,d}$ for each case are not elaborated (they are minor variations of the one shown in Figure 5.7). Results are presented in the next section and show how effective — or ineffective — these conditioning methods really are.

Sequential ordering by recency. This conditioning method was described in the previous chapter, and is simply a time-ordered list of all submissions entered by the user. The first column of Table 6.1 illustrates the sequentially-ordered history list numbered by order of entry. The most recent submission appears on the top, and the history list — as with all other examples on the Table — is intended to be reviewed top-down.

There are two virtues of recency. First, the items presented would be the ones a user has just entered and still remembers. He knows they are on the list without having to scan through it. Second, unlike some adaptive methods, there is no initial startup instability of deciding what to present when only a few items are available.

Sequential *starting in ~/text*	Duplicates Removed *original position*	Duplicates Removed *latest position*	Frequency Order *secondary key is recency*	Frequency Order *secondary key is reverse-recency*
14 cd ~/figs	12 cd ~/text	14 cd ~/figs	10 ls 3	10 ls 3
13 print draft	9 graph fig1	13 print draft	14 cd ~/figs 2	4 edit draft 2
12 cd ~/text	8 edit fig2	12 cd ~/text	13 print draft 2	11 edit fig1 2
11 edit fig1	7 edit fig1	11 edit fig1	11 edit fig1 2	13 print draft 2
10 ls	5 cd ~/figs	10 ls	4 edit draft 2	14 cd ~/figs 2
9 graph fig1	3 print draft	9 graph fig1	12 cd ~/text 1	8 edit fig2 1
8 edit fig2	2 edit draft	8 edit fig2	9 graph fig1 1	9 graph fig1 1
7 edit fig1	1 ls	4 edit draft	8 edit fig2 1	12 cd ~/text 1
6 ls				
5 cd ~/figs				
4 edit draft				
3 print draft				
2 edit draft				
1 ls				

Alphabetic *duplicates removed*	Directory Sensitive *directory context is ~/text*	Directory Sensitive *directory context is ~/figs*	Commands *recency, no duplicates*
14 cd ~/figs	14 cd ~/figs	12 cd ~/text	14 cd
12 cd ~/text	3 print draft	8 edit fig1	13 print
4 edit draft	5 cd ~/figs	10 ls	11 edit
11 edit fig1	4 edit draft	9 graph fig1	10 ls
8 edit fig2	13 print draft	11 edit fig2	9 graph
9 graph fig1	2 edit draft	7 edit fig1	
10 ls	1 ls	6 ls	
13 print draft			

Directory Sensitive, *with duplicates removed, events saved in latest position*

1 ls	8 edit fig2
4 edit draft	9 graph fig1
13 print draft	10 ls
14 cd ~/figs	11 edit fig1
	12 cd ~/text

In Unix, users change directories through the cd *command. The "~" is shorthand for the home directory. Following "/"'s indicate sub-directories.*

Table 6.1: Examples of history lists conditioned by different methods

Pruning duplicates from the history list. The sequentially-ordered history lists mentioned so far maintain a record of every single command line typed. Duplicate lines are not pruned off the list. On a history list of limited length, duplicates occupy space which could more fruitfully be used by other command lines.

There are two obvious strategies for pruning redundancies, as described by Barnes and Bovey (1986). The first saves the activity in its original location on the history list (as in HyperCard's *recent* facility→ §4.1.4) while the second saves it in its latest position (as in *wmw*→ §4.1.2). It is expected that the latter approach would give better performance, as not only is local context maintained, but unique and low-probability command entries will migrate to the back of the list over time[1].

Consider, for example, the two pruned event lists in the second major column of Table 6.1. Both are the same length, which is considerably shorter than the plain sequential one in the first column. But the order of entries are quite different. Even in this short list, the disadvantage of saving items in their original position is evident. Local context is weak (indicated by the scattered event numbers), and the frequently used *ls* command line is poorly positioned at the bottom of the list.

Data sets are re-analyzed using both strategies of pruning duplicates off sequential history lists, where recurring items are either kept in their original position or moved to their latest position.

Frequency ordering. Perhaps the most obvious way of ranking activities is by frequency, where the most often-used command line appears at the front of the history list and the rarest one at the end. This approach is conservative. Old and frequently used items tend to stay around — unless there is a built-in decay factor — while newer submissions will not appear near the head of the list until they are

---

[1]Saving recurrencing activities in their latest position only is equivalent to "self-organized files", where successfully located records are moved to the beginning of the sequentially accessed file. As briefly discussed by Knuth (1973), oft-used items tend to be located near the beginning of the file, and the average number of comparisons is always less than twice the optimal value possible.

repeated as often as the old ones. Still, it may do as well as or perhaps even better than recency.

Although ordering items by frequency is straightforward, it is not clear how to sort items of identical frequencies. One possibility uses recency as the secondary sorting key. For example, if the current submission is a recurrence, its frequency count is increased by 1 and it is relocated before all other recurrences with the same count. Another approach uses a secondary sort by reverse-recency, where the recurring item is placed at the tail of the list of items with identical frequencies. Contrasting these two methods gives a bound to the range of recency effects. Examples of each are shown in Table 6.1, where the number to each item's right counts how often that line has been submitted.

It is expected that frequency ordering may do quite well, given that UNIX command lines often consist of a frequently-executed command without arguments. But probably fewer characters are predicted, since short lines would tend to dominate the higher frequencies. Another disadvantage of frequency order is that counts must now be associated with every submission. At best, this just takes up some space and a little cpu time, which matters little in these days of cheap memory and fast machines. At worst, the derived probabilities associated with a young history list are quite unstable and may lead to very poor initial predictions, which could discourage a new user from placing their faith in it (*cf* recency).

The data sets are analyzed by ordering history lists by frequency and using two cases of secondary sorting: recency and reverse-recency. Since there is no advantage in keeping multiple copies of command lines, they are pruned from the list.

Alphabetic ordering. Sorting activities alphabetically is another possibility. Although items on alphabetic ordered lists are best found by binary search or pattern matching, surprisingly many systems provide only scrolling capabilities for sequential searching. One example is the *wmw*, described in Section 4.1.2, which provides it as a display option (Barnes and Bovey, 1986). We would expect poor performance of a distribution derived from alphabetic ordering. Letter frequencies aside, it should do no better than a random ordering of events. Performance is easily evaluated by seeing how many pages of previous activities would have to be scrolled on average before the desired item is found.

User's traces were re-analyzed by placing their command lines on a history list in ASCII order. If a new submission is identical to one already on the list, it is ignored. An example of an ASCII-ordered list is included in Table 6.1.

Context-sensitive history lists by directory. Users of computer systems perform much task switching (Bannon *et al*, 1983), where each task represents an independent or interacting context. (See Section 8.1 for further discussion.) Since many command line submissions are specific to the task at hand, it is reasonable to hypothesise that context-sensitive history lists will give better local predictions.

Ideally, the reuse facility would infer the context of every submission entered and place it on an appropriate history list, creating a new one if needed. Events common to multiple contexts could perhaps be shared between lists. The system would then infer the likely context of the next submission and offer its predictions for reuse only from the appropriate list.

Associating a user's activities with their tasks or goals is not easy, and such inferences cannot be made reliably. Instead, a simple heuristic provides a reasonable guess of one's true context. UNIX furnishes a hierarchical directory system for maintaining files. As many user actions reference these files, I hypothesize that the current working directory defines a context for command lines. This grouping of command lines by the current directory (or perhaps by the obvious alternative of windows) is just an estimate — possibly a poor one — of actual task contexts.

When data was collected, each user submission was annotated with the directory it was run in. The traces are re-analysed by creating a new history list for each new directory visited and placing the command line on that list. The recurrence distance for each submission is then calculated by retrieving the history list for the current directory of the next submission and searching it for the most recent match.

The second main column in the lower half of Table 6.1 illustrates the directory-sensitive condition applied to the sequential input, where each sub-column is sensitive to a particular directory. Most command lines refer to files in that directory, and would rarely be used in other directories. Some command lines, however, are common to more than one directory (for example, *ls* for listing files).

Ordering commands by recency. Chapter 3 showed that most individuals use few commands, and that the frequency distribution of command selection is very uneven. It would be interesting to see how a history list comprised of recency-ordered commands (not command lines) would perform. Although we expect the probability of a matching prediction $\mathcal{R}_D$ to be quite high, the characters predicted per recurrence would be lower, since the rest of the command line is ignored (see the example in Table 6.1).

User traces are re-analyzed over history lists of commands. Duplicate commands are pruned, with a single copy of the command kept in its position of latest occurrence.

Partial matches. Instead of the next command line matching a previous one exactly, partial matching may be allowed. This is helpful when people make simple spelling mistakes, the same command and options are invoked on different arguments, command lines are extended, and so on.

However, the potential benefit is highly user and situation dependent, for the user must alter the selected sequence before it is invoked. Consider the next submission s and its partial match to a previous event e on the history list. If selecting and modifying *e* is easier and more reliable than entering *s*, then it is an attractive strategy. If *s* is long, for example, and differs from *e* by a single character, selecting and fixing *e* is probably faster. If *s* is short, it is unlikely that the user would bother.

The possibility of the given pattern retrieving an undesired interposed event must be considered too. Consider, for example, a user who wishes to to invoke the document formatter *roff* on the file *file.n* after submitting the following *csh* input lines.

roff file.n
*rm *.n*
edit file.n

The user enters the *csh* reuse directive *!r* which recalls the last event beginning with the letter r, and mistakenly executes *rm *.n* instead of *roff file.n*. All files ending with *.n are removed, and the work is lost.

Partial matches by prefix were investigated. Command lines are matched whenever it is a prefix of the next submission. If $s =$ "*edit fig2*", for example, some partial matches on prefix for *e* could be "*ed*", "*edit*", "*edit fig*", and "*edit fig2*".

In partial matching, history lists are not altered. Rather, it is the definition of recurrence that has changed. Any increase in predictive probability comes at the expense of fewer useful characters predicted. Effects of partial matching are shown for a recency ordered history list both with duplicates retained and with duplicates pruned.

A hierarchy of command lines and command-sensitive sublists. One way of increasing the effectiveness of a history list is by using existing items on the display as a hierarchical entry point to related items. More specifically, consider a history list of command lines where each item can further raise a secondary list of all lines that share the same initial command (called a command-sensitive list). One first scans down i entries in the normal list for either an exact match which terminates the search, or for a line that starts with the desired command. In the later case, the command-sensitive list is displayed (perhaps as a pop-up menu) and the search continues until an exact match is found j entries later. The distance of a matching recurrence is simply $i + j$. Given the sequential list in Table 6.1, for example, the command sensitive sublist on item 11 would be *edit fig1*, *edit fig2*, and *edit draft*.

Such a scheme could do no worse than the original method of displaying the history list, and has potential to do much better. This method was tested by using recency-ordering of both the primary and command-sensitive history lists with duplicates saved in their latest position only.

Combinations. The strategies above are not mutually exclusive, and can be combined in a variety of ways. The bottom half of column 2 of Table 6.1 shows one such possibility, where the event list is conditioned by directory sensitivity and pruning. Data sets were re-analyzed using combinations of a few conditions mentioned above.

6.1.3 Evaluating the conditioning methods

Data Selection. Conditioning by directory context is no different from standard sequential history if subjects only work within a single directory. As not all subjects used multiple directories, this portion of the analysis was restricted to the experienced programmers, each of whom used several directories[2]. All other groups had subjects who used one directory exclusively (17 of the 55 novice programmers, 6 of the 25 non-programmers, and 2 of the 52 computer scientists).

Each subject is re-analyzed using the afore-mentioned conditioning methods and some of their combinations for redefining both the history list and the method

[2]Another reason for limiting the number of subjects analysed is more pragmatic — about 4 to 8 hours of machine time were required to process a single condition for each group.

of determining recurrences.

Length of command lines and M_D. Before delving into details of how each method performs according to the quality metric, we need to determine the best performance possible. To start, the average length of command lines is 7.58 characters, where terminating line feeds are not counted and duplicate lines are included. This was calculated by finding the average line length for each subject, and averaging those results over all subjects. These numbers will under-estimate the actual characters typed, for editing sequences are not included.

Since reuse facilities can only predict lines that have been entered previously, it is important to know if recurring lines have a different average length than those appearing only once. Further analysis shows that the average length of submissions that already exist on the history list is 5.97 characters, while those that appear for the first time are 12.29 characters long. This is not as surprising as it might seem at first, for short lines with few arguments are usually more general-purpose (and therefore reusable) than complex lines. We would expect frequently-appearing lines to be shorter than lines that are rarely or never repeated.

The maximum possible value for M_D is therefore $\mathcal{R} * 5.97/100$, for M_D is calculated over all submissions. As $\mathcal{R}$ is 74.4% for experienced programmers, M_D for an optimal conditioning method is 4.43 characters predicted per submission.

Results. Results for all conditions are summarized in four tables, each presenting various distributions over the last fifty items of the history list. Table 6.2 presents the percent frequency of submissions recurring at a particular distance ($\mathcal{R}_d$), while Table 6.3 provides the same information as a running sum over distance ($\mathcal{R}_D$). The latter includes the total recurrence rate over the complete history list, which differs with certain conditions[3]. Figure 6.1 graphs the results of Table 6.3. As with Figure 5.8b, the horizontal axis shows the position of the repeated command line on the history list relative to the current one, while the vertical axis represents $\mathcal{R}_D$, the rate of accumulated command line recurrences, as a percentage.

The next two tables involve the length in characters of recurrences. Table 6.4 shows the average number of characters saved for a recurrence at a given distance (the value of $\bar{c}_d$). Table 6.5 displays the metric M_D, which shows how many characters are saved for an average submission. This value accounts for recurring and non-recurring submissions, and assumes that the user can select from D predictions. Figure 6.2 graphs the performance of each conditioning method over distance using this metric.

Standard sequential. The last chapter saw an $\mathcal{R}_{D_{10}}$ of 44.4% for the experienced programmer group (also in Table 6.3). The metric $M_{D_{10}}$ for the same group is 2.48 characters per submission (Table 6.5), which is 55% of the maximum value it could have. These figures will be used as a benchmark for comparing other conditioning methods.

Pruning duplicates. Although pruning duplicates off the history list does not alter the recurrence rate, it does shorten the total distance covered by the distribution (*ie* the history list is smaller). First, how does saving single copies of recurring activities in their original position on the history list compare with saving items in their latest position? A quick glance at the tables and graphs shows that the former gives exceedingly poor predictive performance. Curiously, saving activities in their original position gave a much higher average length of predicted strings than any other conditioning method for lines recurring over small distances (Table 6.4). But

[3]The recurrence rate differs when the way of determining matching submissions changes (partial matching, commands only) and when the history list is split into multiple lists (directory sensitivity).

Probability of a recurrence at the given distance d in percent ($\mathcal{R}_d$)														
Conditioning method	Distance 1	2	3	4	5	6	7	8	9	10	20	30	40	50
Recency, duplicates saved:														
always	6.12	12.29	6.71	4.83	4.12	2.94	2.36	1.97	1.66	1.40	0.59	0.32	0.21	0.16
in original position only	2.53	1.75	1.30	1.08	1.01	0.82	0.79	0.66	0.75	0.61	0.35	0.34	0.32	0.23
in latest position only	6.12	12.82	7.58	5.35	4.93	3.48	2.83	2.38	1.99	1.70	0.59	0.30	0.18	0.14
Frequency order:														
second key recency	13.13	7.95	5.24	3.98	3.37	2.83	2.47	2.11	1.79	1.56	0.73	0.49	0.26	0.20
second key reverse recency	13.16	7.74	5.16	3.84	3.20	2.74	2.38	1.91	1.73	1.53	0.74	0.44	0.24	0.16
Alphabetic order:														
duplicates removed	1.27	1.00	1.21	1.30	1.02	1.25	0.76	0.87	0.85	0.57	0.68	0.48	0.32	0.52
Directory sensitive by recency:														
duplicates included	7.46	13.61	8.20	4.89	3.50	2.73	2.06	1.67	1.52	1.22	0.44	0.28	0.15	0.12
duplicates removed	7.46	14.29	9.39	5.78	4.13	3.11	2.37	2.06	1.53	1.38	0.39	0.18	0.11	0.08
Commands only by recency:														
duplicates removed	15.36	19.87	10.89	7.05	5.75	4.09	3.11	2.56	2.21	1.81	0.64	0.28	0.16	0.14
Partial matching by recency:														
duplicates included	8.17	13.49	7.61	5.45	4.51	3.35	2.60	2.18	1.85	1.59	0.63	0.34	0.26	0.16
duplicates removed	8.17	14.07	8.60	6.07	5.34	3.89	3.06	2.64	2.26	1.92	0.65	0.33	0.23	0.18
Command hierarchy:														
recency, duplicates removed	6.12	13.89	9.35	6.60	5.56	4.03	3.19	2.70	2.26	1.83	0.52	0.22	0.13	0.09

Table 6.2: Probability of a recurrence over distance for various conditioning methods

Conditioning method	Cumulative probabilities of a recurrence up to a given distance d in percent ($\mathcal{R}_D$)														
	Distance														$\mathcal{R}$
	1	2	3	4	5	6	7	8	9	10	20	30	40	50	
Recency, duplicates saved:															
always	6.12	18.41	25.12	29.94	34.06	37.00	39.36	41.33	42.99	44.39	52.67	56.82	59.58	61.47	74.42
in original position only	2.53	4.28	5.57	6.65	7.66	8.48	9.27	9.93	10.68	11.29	15.92	19.58	22.82	26.29	74.42
in latest position only	6.12	18.94	26.52	31.87	36.80	40.28	43.11	45.48	47.47	49.17	58.98	63.51	66.00	67.67	74.42
Frequency order:															
second key recency	13.13	21.08	26.32	30.29	33.66	36.48	38.95	41.06	42.85	44.41	55.35	60.98	64.31	66.48	74.42
second key reverse recency	13.16	20.89	26.05	29.90	33.09	35.83	38.21	40.12	41.84	43.37	53.63	58.85	62.02	63.93	74.42
Alphabetic order:															
duplicates removed	1.27	2.27	3.48	4.78	5.80	7.05	7.81	8.68	9.52	10.09	16.53	21.76	25.84	30.16	74.42
Directory sensitive by recency:															
duplicates included	7.46	21.07	29.27	34.16	37.66	40.39	42.44	44.12	45.63	46.85	53.52	56.62	58.48	59.69	65.53
duplicates removed	7.46	21.75	31.15	36.93	41.06	44.18	46.54	48.60	50.13	51.51	58.80	61.56	62.93	63.74	65.53
Commands only by recency:															
duplicates removed	15.36	35.23	46.12	53.17	58.92	63.01	66.12	68.68	70.89	72.70	82.61	86.83	89.05	90.49	95.24
Partial matching by recency:															
duplicates included	8.17	21.65	29.26	34.71	39.22	42.57	45.17	47.34	49.19	50.78	60.16	64.74	67.78	69.93	84.39
duplicates removed	8.17	22.23	30.83	36.90	42.25	46.14	49.20	51.84	54.10	56.02	66.90	72.04	74.94	76.88	84.39
Command hierarchy:															
recency, duplicates removed	6.12	20.01	29.36	35.96	41.52	45.56	48.74	51.44	53.71	55.54	64.81	68.38	70.17	71.21	74.42

Table 6.3: Cumulative probabilities of a recurrence over distance for various conditioning methods

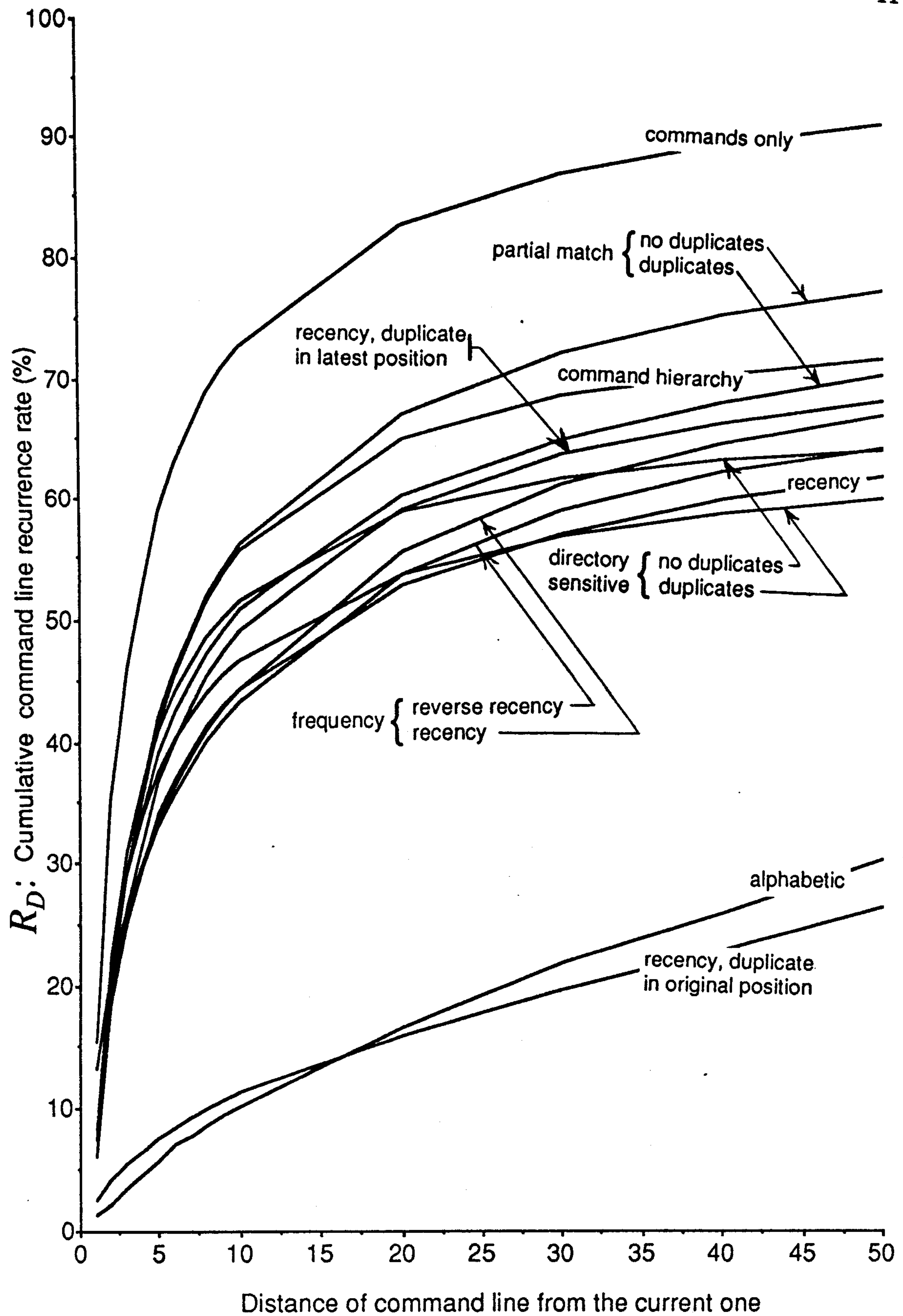


Figure 6.1: Cumulative probabilities of a recurrence over distance for various conditioning methods

The average number of characters saved over all subjects per recurrence at a given distance ($\bar{c}_d$)														
Conditioning method	Distance													
	1	2	3	4	5	6	7	8	9	10	20	30	40	50
Recency, duplicates saved:														
always	5.94	5.04	5.31	5.57	5.79	5.61	6.11	5.84	5.64	5.51	6.26	5.39	4.83	5.78
in original position only	10.60	10.24	9.76	9.51	8.41	8.83	9.49	7.97	8.17	8.00	7.18	6.70	6.11	5.42
in latest position only	5.94	5.06	5.49	5.72	5.86	5.51	5.88	5.76	5.74	5.87	6.21	5.83	5.31	5.67
Frequency order:														
second key recency	2.57	3.94	5.34	5.76	5.30	5.58	5.17	6.10	6.45	6.50	6.91	7.61	8.73	8.94
second key reverse recency	2.60	3.93	5.35	5.65	5.10	5.56	5.30	6.19	6.08	6.38	7.31	7.58	7.30	8.15
Alphabetic order:														
duplicates removed	3.52	6.67	5.67	5.66	5.66	7.09	6.12	7.10	6.90	6.79	6.33	4.65	5.97	4.84
Directory sensitive by recency:														
duplicates included	6.47	5.70	5.62	5.95	6.24	6.08	6.56	6.14	5.61	5.69	6.08	6.17	5.23	5.08
duplicates removed	6.47	5.71	5.76	6.10	6.14	6.05	6.21	6.04	5.88	5.98	6.43	4.81	6.04	4.36
Commands only by recency:														
duplicates removed	3.25	2.68	2.82	2.96	3.08	3.00	3.07	3.05	3.06	3.15	2.96	3.05	2.78	2.98
Partial matching by recency:														
duplicates included	5.54	4.86	5.02	5.18	5.32	5.22	5.45	5.02	4.94	4.90	5.24	4.09	4.30	3.99
duplicates removed	5.54	4.87	5.18	5.25	5.38	4.99	5.14	5.02	4.99	5.11	4.65	4.27	3.84	4.00
Command hierarchy:														
recency, duplicates removed	5.94	5.36	5.85	6.11	6.15	6.23	6.02	6.11	6.30	6.48	5.91	6.33	4.44	4.37

Table 6.4: Average number of characters saved over distance per recurrence

Cumulative average savings in characters of D predictions over all submissions (M_D)														
Conditioning method	Distance													
	1	2	3	4	5	6	7	8	9	10	20	30	40	50
Recency, duplicates saved:														
always	0.37	0.99	1.35	1.63	1.87	2.04	2.19	2.31	2.40	2.48	2.99	3.25	3.43	3.55
in original position only	0.27	0.46	0.59	0.69	0.78	0.86	0.94	0.99	1.05	1.10	1.48	1.75	1.98	2.20
in latest position only	0.37	1.02	1.44	1.76	2.05	2.25	2.42	2.56	2.68	2.78	3.40	3.69	3.86	3.98
Frequency order:														
second key recency	0.32	0.64	0.93	1.16	1.34	1.49	1.62	1.75	1.86	1.96	2.74	3.19	3.49	3.68
second key reverse recency	0.33	0.63	0.91	1.14	1.30	1.45	1.57	1.69	1.79	1.89	2.50	2.99	3.26	3.43
Alphabetic order:														
duplicates removed	0.03	0.08	0.15	0.24	0.31	0.43	0.48	0.54	0.61	0.65	1.12	1.45	1.69	1.91
Directory sensitive by recency:														
duplicates included	0.48	1.28	1.76	2.05	2.27	2.44	2.57	2.67	2.76	2.83	3.25	3.45	3.57	3.65
duplicates removed	0.48	1.32	1.88	2.24	2.45	2.68	2.83	2.95	3.04	3.13	3.59	3.77	3.87	3.93
Commands only by recency:														
duplicates removed	0.50	1.03	1.34	1.55	1.73	1.86	1.95	2.03	2.10	2.15	2.46	2.59	2.67	2.71
Partial matching by recency:														
duplicates included	0.45	1.11	1.50	1.79	2.04	2.21	2.36	2.47	2.56	2.64	3.12	3.35	3.51	3.62
duplicates removed	0.45	1.14	1.60	1.93	2.21	2.41	2.57	2.71	2.82	2.92	3.47	3.72	3.86	3.96
Command hierarchy:														
recency, duplicates removed	0.37	1.11	1.68	2.09	2.43	2.68	2.88	3.04	3.18	3.30	3.90	4.12	4.23	4.29

Table 6.5: Cumualtive average number of characters saved per submission over distance

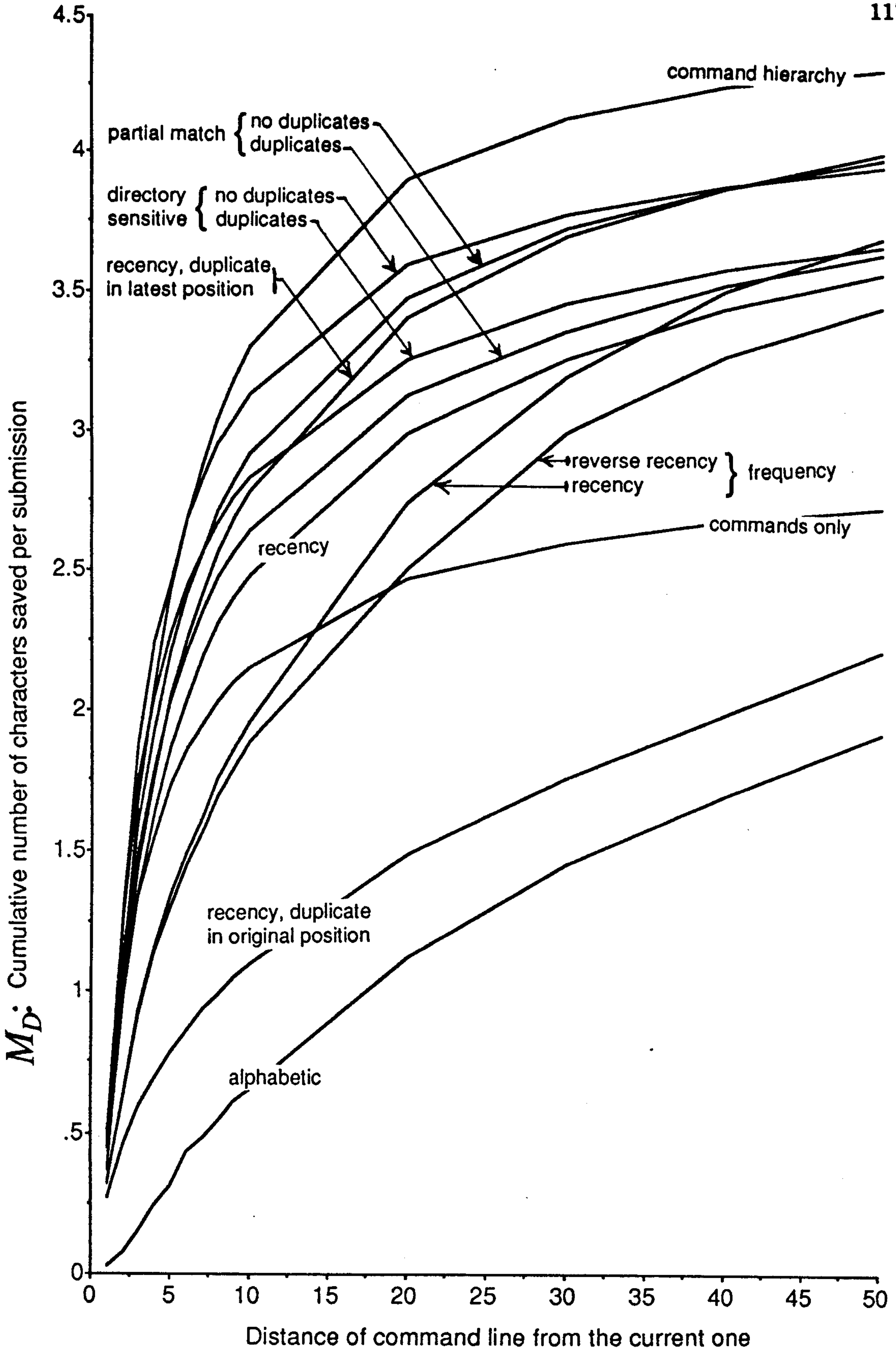


Figure 6.2: Cumulative average number of characters saved per submission over distance

it is the low-frequency lines that must contribute most to this average, as high-frequency ones do not remain near the front of the list. This larger than expected line length supports the hypothesis that oft-repeated lines are shorter on average than rarely repeated ones. The low probability values associated with those recurrences reduce any benefit accrued by predicting longer lines. Consider a 10-item working set. The probabilities $\mathcal{R}_{D_{10}}$ of a recurrence falling in that set are 11% and 49% for the original and the latest position respectively, and the corresponding values of $M_{D_{10}}$ are 1.10 and 2.78 characters per submission. Saving activities in their original position is clearly ineffective. The remainder of this dissertation assumes that history lists with duplicates pruned will save the single copy in its position of latest occurrence.

As the working set size increases, so does the value of $\mathcal{R}_D$ associated with a duplicates-pruned list when compared to the standard sequential list (Table 6.3 and Figure 6.3). Pruning duplicates increases the overall probability of a ten-item working set by 4.8% ($\mathcal{R}_{D_{10}} = 49.1\%$ vs 44.4%), and $M_{D_{10}}$ is increased by 0.3 characters per submission.

Frequency order. Using recency as a secondary sort in a frequency-ordered list is marginally better than sorting by reverse-recency. The overall probability of a ten-item working set is 1.1% higher, and 0.1 character more is predicted per submission. Since these reflect the bounds of these two conditions, it is hardly worth worrying about how to do the secondary sort. Still, whenever frequency-ordered lists are discussed in the dissertation, the better secondary sort of recency is assumed.

Frequency-ordered history lists do not do as well as strict sequential ones, even though duplicates are not included in the former. Although the probability of a hit in a ten-item working set is about the same ($\mathcal{R}_{D_{10}} = 44.4\%$), lines predicted are shorter (as expected). The metric $M_{D_{10}}$ is 0.6 characters less per submisson.

Alphabetic order. As anticipated, alphabetic ordering of history lists gives the poorest performance of any conditioning technique (this assumes sequential searching through the list). With a ten-item display, $\mathcal{R}_{D_{10}} = 10.1\%$, and only 0.65 characters are predicted per submission. If a user were scrolling through this display, fully 100 items (or ten pages) must be reviewed on average to match $M_{D_{10}}$ for the strict sequential list!

Context-sensitive history lists by directory. Creating context-sensitive directory lists with duplicates retained decreases the overall recurrence rate for experienced programmers from 74.4% in the strict sequential case to 65.5%, because command lines entered in one directory are no longer available in others. Although this reduction means that plain sequential lists out-perform directory-sensitive ones over all previous entries, benefits were observed over small working sets. As Table 6.2 illustrates, the first three directory-sensitive items are more probable than their sequential counterparts, approximately equal for the fourth, and slightly less likely thereafter. The accumulated probabilities $\mathcal{R}_D$ cross over with a working set of twenty-seven items (Figure 6.1). With a working set of ten items, directory-sensitivity increases the overall probability that the next item will be in that set by 2.5% ($\mathcal{R}_{D_{10}} = 46.9\%$). The length of lines predicted in the directory sensitive condition are also longer than those predicted by a strict sequential list, and $M_{D_{10}}$ is 0.35 characters per submission higher.

Ordering commands by recency. When all aspects of a command line are ignored except for the initial command word, the recurrence rate jumps to 95.2%. The accumulated probabilities of recurrences are also very high when compared to the strict sequential list — $\mathcal{R}_{D_{10}} = 72.7\%$ *vs* 44.4%. But the high predictability is offset by the low number of characters predicted. $M_{D_{10}}$ actually drops 0.3 characters per prediction.

Partial matches. Pattern matching by prefix increases the recurrence rate to 84.4%, where the recurrence rate is now defined as the probability that any previous event is a prefix of the current one. As partial matches are found before more distant (and perhaps non-existent) exact matches, an increase is expected in the rate of growth of the cumulative probability distribution. This increase is illustrated in Table 6.3 and Figure 6.1. Conditioning by partial matching increases $\mathcal{R}_{D_{10}}$ of a ten-item working set by 6.4% when compared to a strict sequential list (Table 6.3), although lines predicted are shorter (Table 6.4). Still, $M_{D_{10}}$ is increased slightly by 0.16 characters per submission.

A hierarchy of command lines and command-sensitive sublists. The history list comprised of recency-ordered non-duplicated lines and command-sensitive sublists shows the best performance of all conditions evaluated. The accumulated probability of a ten-item display is $\mathcal{R}_{D_{10}} = 55.5\%$ out of the 74.4% possible. $M_{D_{10}}$ is 3.3 characters per submission, compared to the 4.4 character maximum for an optimal system.

Combinations. When conditioning methods are combined, the effects are slightly less than additive. A few possible combinations are included by removing duplicates from both the directory-sensitive and partial matching conditions. Each improves as expected, as illustrated by Tables 6.2 through 6.5 and Figures 6.1 and 6.2. Where feasible, conditioning methods can be combined even further. For example, a partially-matched, pruned and directory sensitive history mechanism increases $\mathcal{R}_{D_{10}}$ over a strict sequential one by 12.7% with a working set of ten items (reported in Greenberg and Witten, 1988a).

6.1.4 Discussion

The recurrence rate $\mathcal{R}$ provides a theoretical ceiling on the performance of a reuse facility using literal matches. It is reached only if one reuses old submissions at every opportunity. However, finding and selecting items for reuse could well be more work than entering it afresh, especially if it is necessary to search the complete history list. Pragmatic considerations mean that most reuse facilities choose a small set of previous submissions as predictions, and offer only those for reuse. While the last chapter demonstrated that temporal recency is a reasonable predictor, the conditioning methods described and evaluated here proved that a few simple strategies can increase predictive power even further.

We saw that up to 55% of all user activity can be successfully predicted with working sets of ten predictions for literal matches, depending upon the conditioning method chosen. Given that $\mathcal{R} = 75\%$ on average, which is the best a perfect literal reuse facility could do, this means that the best predictive method described here is about 75% effective, at least potentially.

When the quality metric is incorporated, we observe that the best method correctly predicts 3.3 characters per submission (with a working set of 10 items), compared to the 4.4 optimum calculated previously. Again, the method is about 75% effective.

In marked contrast, a few conditioning methods perform poorly. Saving duplicates in their original position has no benefit, and alphabetic ordering of the history list is questionable. Although frequency ordering does not fare badly, other methods give better results.

There is no guarantee that any of the conditioning methods describe here will be effective in practice, for the cognitive and mechanical work required for finding and selecting items for reuse from even a small list may still be too costly. Research is required in three areas. First, other conditioning methods should be explored that further increase the probability of a set of predictions (up to the value of $\mathcal{R}$). One candidate could use a model similar to that used by the *Reactive Keyboard* (Darragh, 1988) → §4.2.2. Second, the size of the working set should be reduced. Ideally, only one correct prediction will be suggested. Third, the cognitive effort required for reviewing a particular conditioned set of predictions must be evaluated. One factor is whether the user knows beforehand if the item being sought appears in the set, otherwise he may face an exhaustive and ultimately fruitless search. Another factor is whether the item can be found rapidly. Given these factors, it is possible that one conditioning technique may give better practical performance than another, theoretically superior, one.

6.2 Actual use of Unix history

We have seen that user dialogues are highly repetitive and the last few command lines have a high chance of recurring — the premise behind most history systems. There are certainly plenty of opportunities for reuse, especially when appropriate conditioning methods are engineered into the presentation of items. But are current history mechanisms used well in practice? And how are they used? This was investigated by analyzing each user's *csh* history use. During data collection, all *csh* history uses were noted, although the actual form of use was not. Results should be interpreted carefully, for they may be artifacts arising from idiosyncrasies of the *csh* facilities, rather than from fundamental characteristics of reuse.

The recurrence rate and its probability distribution, studied previously, give a theoretical value against which to assess how effectively history mechanisms are used in practice. The average rate of re-selecting items through a true sequential history list (as used by *csh*) cannot exceed the average value of $\mathcal{R}$, which was found to be 74%. By comparing the user's actual re-selection rate with this maximum, the practical effectiveness of a particular history mechanism can be judged.

Sample Name	Users of History actual	(%)	Mean rate of history uses (%)
Novice Programmers	11/55	20%	2.03
Experienced Programmers	33/36	92%	4.23
Computer Scientists	37/52	71%	4.04
Non-Programmers	9/25	36%	4.35
Total	90/168	54%	3.89

Table 6.6: History uses by sample groups

6.2.1 Results

Table 6.6 shows how many users of UNIX *csh* in each sample group actually used history. Although 54% of all users recalled at least one previous action, this figure is dominated by the computer sophisticates. Only 20% of Novice Programmers and 36% of Non-Programmers used history, compared to 71% for Computer Scientists and 92% for Experienced Programmers.

Those who made use of history did so rarely. On average, 3.9% of command lines referred to an item through history, although there was great variation (*std dev* = 3.8; *range* = 0.05% – 17.5%). This average rate varied slightly across groups, as illustrated in Table 6.6, but an analysis of variance indicated that differences are not statistically significant ($F(3,86) = 1.02$).

In practice, users did not normally refer very far back into history. With the exception of novices, an average of 79 – 86% of all history uses referred to the last five command lines. Novice Programmers achieved this range within the last two submissions. Figure 6.3a illustrates the nearsighted view into the past. Each line is the running sum of the percent of history use accounted for (the vertical axis) when matched against the distance back in the command line sequence (the horizontal axis). The differences between groups for the last few actions (left-hand side of the

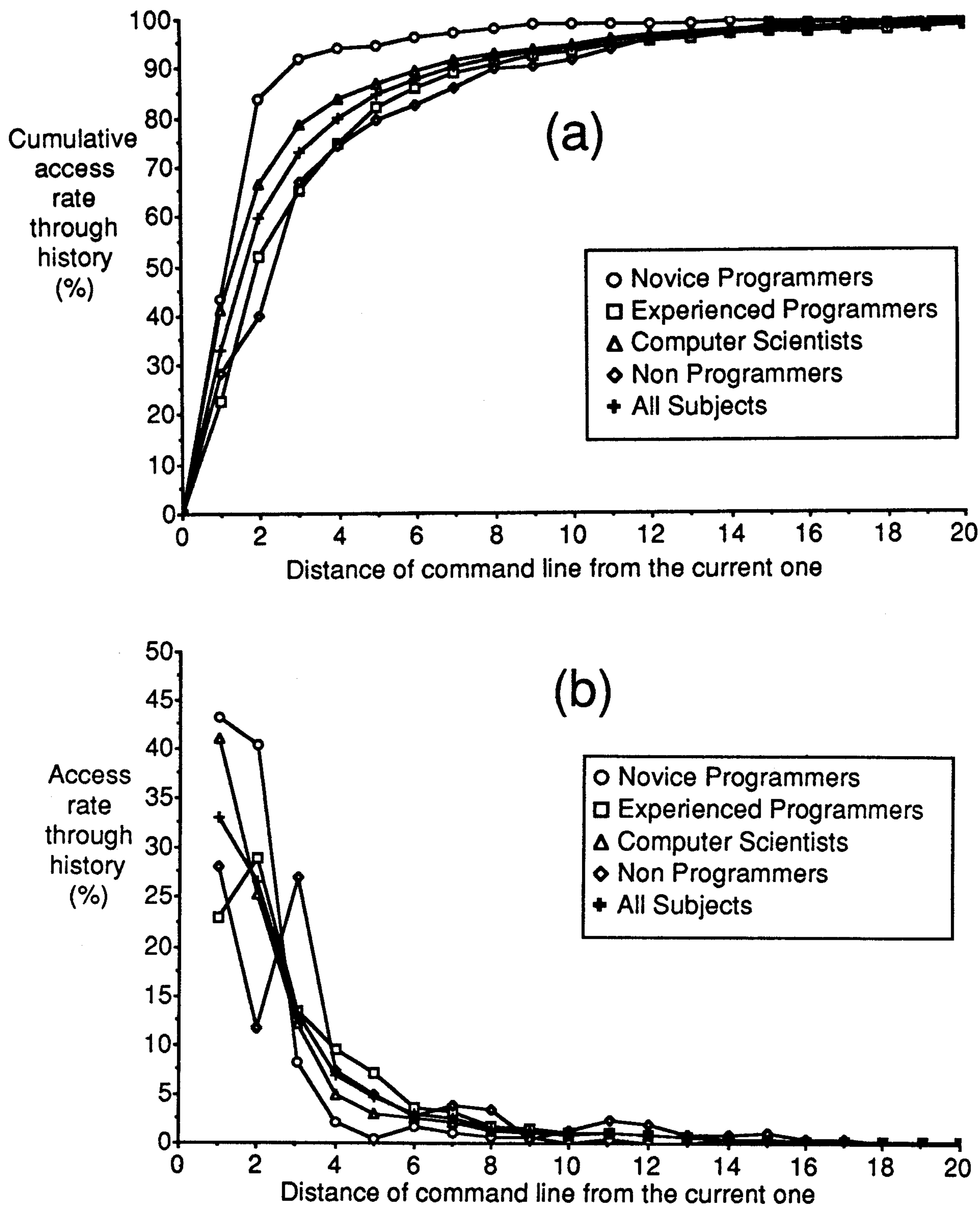


Figure 6.3: a) Cumulative distribution of history; and b) distribution of history use as a measure of distance

graph) reflect how far back each prefers to see[4].

Since most activities revolve around the last few submissions, the distribution bears closer examination. The data points in Figure 6.3b now represent the percent of history use accounted for by each reference back. High variation between groups is evident. Although most uses of history recall the last or second last entry, it is unclear which is referred to more.

It was also noticed that history was generally used to access or slightly modify the same small set of command lines repeatedly within a login session. If history was used to recall a command line, it was highly probable that subsequent history recalls will be to the same command.

A few *csh* users were queried about history use. They indicated that they are discouraged from using *csh* history by its difficult syntax and the fact that previous events are not normally kept on display. (The latter point is important, for it enforces the belief that candidates for reuse should be kept on a display.) Users also stated that most of their knowledge of UNIX history was initially learnt from other people — the manual was incomprehensible. Also, the typing overhead necessary to specify all but the simplest retrievals makes them feel that it is not worth the bother.

6.2.2 Corroboration and extensions

Another researcher, Alison Lee, also examined history usage within various command interpreters available to the UNIX environment. Some of her qualitative findings corroborate and add to the observations noted in this section (Lee, 1988a).

[4]Actual figures are probably higher than those indicated here, due to inaccuracies in distance estimates. As the *csh* monitor only noted that history was used and not how it was used, the actual event retrieved was determined by searching backwards for the first event exactly matching the current submission. If the submission was a modified form of the actual recalled event, the search would terminate on the wrong entry. I assume that these are a small percent of the total.

1. There were very few uses of *csh* history.
2. Those uses made were of the simpler features, the most popular being "!!" (retrieve the last event) and "!pattern" (retrieve the most recent event beginning with the given pattern).
3. People rarely retrieved items by absolute or relative event number.
4. Although the history list is available for viewing by special request, users rarely asked to see it.
5. Modifiers for editing were rarely used. When used, they tended to be of the form $\wedge pattern1 \wedge pattern2 \wedge$, which does simple substring replacement on the previous submission.
6. Other observed ways of modifying events were by using recalled events as prefixes or suffixes. This technique allows one to add more parameters to previous events or to add a new command sequence in a pipeline.
7. Occasional uses were noted of recalling the last word in the previous event (ie !$) and of printing events without executing them.

Lee also looked at *tcsh*, another history mechanism available to UNIX users that uses a very simple and familiar *emacs*-like editing paradigm to retrieve, review and edit previous events. Although better use of history is expected due to the improved editing power and visualization of the history list, only a marginal increase was noted (although the still-available *csh* history was used less). The visual scrolling and editing capabilities available in *tcsh* were used to some extent.

6.2.3 Discussion

Many people never use UNIX *csh* history. Those who do tend to be sophisticated UNIX users. Yet even they do not use it much. On average, less than 4% of all submissions were retrieved through history out of the 74% potentially possible. The history facility supplied by *csh* is obviously poor.

Some reasons for the failure of *csh* history follow. First, the complex and arcane syntax discourages its use. Those who did use history indicated that only the simplest features of UNIX history were selected. As one subject noted, "it takes more time to think up the complex syntactic form than it does to simply retype the command." Also, it takes at least two or more characters to recall an event in *csh*. As most simple UNIX recurrences are short (6 characters on average), users feel that it is not worth the bother. Second, it is hard to find out about it. *Csh* details are buried in a single on-line manual entry that runs to thirty-one pages(!), the text is quite technical, and examples are sparse. Third, the event list is usually invisible. As previous events are not normally kept on the display, frailty of human memory usually limits recall to the last few items. These deficiencies of *csh* hit Novice Programmers especially hard. Even though they have the highest recurrence rate of all groups and could benefit the most from history, they are effectively excluded from using it.

It is too soon to condemn the ideas provided by *csh*, because some of the observations are likely artifacts of using a poorly designed facility, rather than a human difficulty with the idea itself. Still, it is worthwhile reviewing some of the common history methods used for their benefits and detractions.

Retrieval through absolute or relative position. It is fairly difficult to associate and remember the number of a previous event, as it is an indirect reference. Visibly tagging events with numbers offers benefit only for those interfaces without direct selection and only when no better strategy is available. Perhaps its only viable use is as a redundant way of retrieving events when other selection methods are available.

Scrolling and hidden views. If events are not on display, they will not be asked for. Hidden history lists were rarely recalled, and little use was made of the scrolling facilities in *tcsh*.

Pattern matching. Simple pattern matching, especially by prefix specification, seems promising as a textual way of retrieving events. But matching is potentially dangerous, as users may accidentally retrieve and execute an interposed but undesired event which fits the specification.

Simple methods for recall/selection of very recent events. The syntactically simplest methods are used most to recall very recent events. For example, the "!!" directive was heavily used, even though it does not recall the most probable event. This likely reflects the shortness of short-term memory — users only use "!!" because the last item is the only thing they can both remember reliably and retrieve quickly. Overloading a reuse facility with complex functionality would not make it better.

Editing events. Although people do edit command lines as they compose them, they may not be willing to modify previous events much. Often the cognitive and physical overhead of recall and editing previous events makes simple re-entry more effective. Still, some editing does occur and probably has some value.

Concluding remarks

The first part of this chapter explored further the potential opportunities for reuse in the UNIX *csh*. In particular, a variety of conditioning methods were described and evaluated. Each method used differing strategies for choosing a small set of previous submissions as predictions of the next one. We saw that up to 55% of all user activity and 3.3 characters per submission can be predicted successfully with working sets of just ten predictions. The best any literal predictive method could do is $\mathcal{R} = 75\%$ on average, or 4.4 characters per submission. Although conditioning methods are about 75% effective, there is still considerable room for improvement.

The number of characters saved per submission may seem quite small. The skeptic would conclude that reuse facilities are perhaps not worth the fuss. But a few points should be considered. First, the number of characters saved in practice would be considerably higher, for the string is already formed and editing is not necessary. Actual savings are likely double the theoretical ones (Whiteside, Archer, Wixon and Good, 1982). Second, recognizing and selecting an activity is generally considered easier than recalling or regenerating it. Third, it may all depend upon the user's focus of attention. If he is selecting items from a history list with (say) a mouse, he may continue to do so rather than switch to the keyboard. The reverse is also true.

In marked contrast, the second part of this chapter discovered that *csh* history is used poorly in practice. Most people, particularly those who are not computer sophisticates, do not use it. Those who do, use it rarely. Only 4% of all activity was reused, compared to the 75% possible! And in spite of the esoteric features available in *csh* history, only the simpler features were used with any regularity. It was suggested that the results observed are likely artifacts of using a poorly designed facility, rather than a human difficulty with the idea of reuse.

Chapter 7

Principles, Corroboration and Justification

The two preceding chapters analyzed command line recurrences with dialogs with the UNIX *csh*. Based on the empirical results, the first section of this chapter formulates general principles which characterize how users repeat their activities on computers. Some guidelines are also tabulated for designing a reuse facility that allows users to take advantage of their previous transaction history. The second section corroborates these principles by a *post hoc* study of user traces obtained from another quite different command-line system. The final section steps back from the empirical findings and presents a broader view of reuse.

7.1 Principles and guidelines

This sections abstracts empirical principles governing how people repeat their activities from the UNIX study described earlier. They are summarized and reformulated in Table 7.1 as empirically-based general guidelines for the design of reuse facilities. Although there is no guarantee that these guidelines generalize to all recurrent sys-

Design Guidelines
⊙ Users should be able to recall previous entries.
⊙ It should be cheaper, in terms of mechanical and cognitive activity, to recall items than to re-enter them.
⊙ Simple reselection of the previous five to ten submissions provides a reasonable working set of possibilities.
⊙ Conditioning of the history list, particularly by pruning duplicates and by further hierarchical structuring, could increase its effectiveness.
⊙ History is not effective for all possible recalls, since it only lists a few previous events. Alternative strategies must be supported.
⊙ Events already recalled through history by the user should be easily reselected.

Table 7.1: Design Guidelines for reuse facilities

tems, they do provide a more principled design approach than uninformed intuition.

7.1.1 Principles: How users repeat their activities

A substantial portion of each user's previous activities are repeated. In spite of the large number of options and arguments that could qualify a command, command lines in UNIX *csh* are repeated surprisingly often by all classes of users. On average, three out of every four command lines entered by the user have already appeared previously. UNIX is classified as a recurrent system by the definition in Section 5.1.

This high degree of repetition justifies the intent of reuse facilities. Recurring inputs should be re-entered more easily than the user's original entry, with the aim of reducing both physical tedium and the cognitive overhead of remembering past inputs. Reuse facilities should not be targetted only to experts, as they can help everyone.

New activities are composed regularly. Although many activites are repeated, a substantial proportion are new. One out of every four command lines entered to UNIX *csh* are new submissions. Composing command lines is an open-ended activity.

Many modern interfaces provide transient menus as a way of structuring and packaging common activities. Though useful for appliance-oriented systems→ §1.2.2, this package of favoured submissions will not suffice as a front end to the general-purpose environments addressed by this dissertation. Although the few facilities shared by users should be somehow enhanced, user composition of new command lines must be supported as well.

Users exhibit considerable temporal recency in activity reuse. The major contributions to the recurrence distribution are provided by the last few command lines entered.

As shown in Chapter 4, most reuse facilities are history mechanisms designed to facilitate re-entry of the last few inputs. Systems that do not have explicit and separate displays of the event list rely on a user remembering his own recent submissions, or on the visibility of the dialog transcript on the (usually small) screen. Given the high recency effect, we do expect limited success by memory alone. Yet the principle does pinpoint design weaknesses of existing systems.

First, the second to last command line recurs more often than any other single input. But many reuse facilities favour access to the last entry instead. For example, typing the shortcuts "redo" and "!!" in the Programmer's Assistant and UNIX *csh* respectively defaults to the previous submission, and it is slightly harder to retrieve other items. In history through editing, a user would have to search through two previous mixings of input and output before finding the second to last entry.

Second, the major contributions to the recurrence distribution are provided by the previous 7 ± 3 inputs. Yet most graphical history mechanisms display considerably more than ten events. HISTMENU, for example, defaults to 51 items, and *wmw* is illustrated with 18 slots→ §4.1.2. Considering the high cost of real estate on even large screens, and the user's cognitive overhead of scanning the possibilities, a lengthy list is unlikely to be worthwhile. For example, a menu of the previous ten UNIX events covers, on average, 45% of all inputs. Doubling this to twenty items increases the probability by only 5%.

The cost/benefit tradeoff of encompassing more distant submissions could also be used to tune other predictive systems that build more complex models of all inputs→ §4.2. The high recency effect associated with recurrences suggests that a reasonable number of successful predictions can be formed on the basis of a short memory. Perhaps a recency-based short-term memory combined with a frequency-based long-term memory could generate better predictions.

Some user activities remain outside a small local working set of recent submissions. A significant number of recurrences are not covered by the last few items (about 40% of the recurring total with a working set of ten events). Doubling or even tripling the size of the set does not increase this coverage much, as all but the few recent items are, for practical purposes, equiprobable.

Unfortunately it is just these items that could help the user most. Since their previous invocation happened long ago, they are probably more difficult to remember and reconstruct than more recent activities. If the command line is complex, file names would be reviewed, details of command options looked up in a manual, and so on. Excepting systems with pattern-matching capabilities and scrolling — both questionable methods of recall — no implemented reuse facility provides reasonable ways of accessing distant events. Chapter 8 will explore a few alternative strategies.

Working sets can be improved by suitable conditioning. A perfect "history oracle" would always predict the next command line correctly, if it was a repeat of a previous one. As no such oracle exists, we can only contemplate and evaluate methods that offer the user reasonable candidates for re-selection. Although simply looking at the last few activities is reasonably effective — 60% of all recurrences are covered by the previous ten activities — pruning duplicates, context sensitivity, partial matches, and hierarchies of command-sensitive sublists all increase coverage to some degree. Combining these methods is also fruitful. But they have drawbacks too.

Pruning duplicates increases the coverage of a fixed-size list. However, if sequences of several events can be selected (as in the Programmer's Assistant→ §4.1.1), pruning may destroy useful sequences. And events no longer follow the true execution order, confounding attempts to recall them by position. Pruning problems also arise when the history list serves other purposes. Consider, for example, the undo facility in the Programmer's Assistant. As side effects of activities are stored along with the text of the activity, undoing two textually equivalent items may have different results. In this case, items cannot be pruned without compromising the integrity of the undo operation (Thimbleby, in press).

Conditioning the working set on the current working directory may eliminate useful context-independent items from the history list with only a slight gain in predictive power. But the usefulness of references may improve, since viewing the history list may help remind the user of the specialized and perhaps more complex directives submitted in that context.

Retrieval by partial matching allows a user to select any event and edit it for spelling corrections or minor changes. There is no guarantee that the editing overhead will be less than simple re-entry. The possibility of erroneously retrieving an undesired event must be considered too.

When command-sensitive sublists are included but ignored, the potential for reuse is still as least as high as the primary list. Using the attached sublists can only increase the chance of finding a correct match. Still, these sublists involve considerably more mechanical overhead for reuse unless they are on permanent display, and even then there is a cognitive overhead.

Some seemingly obvious or previously implemented ways of presenting predictions do poorly. Scrolling through alphabetically-sorted submissions is ill-suited to activity reuse. Yet this scheme pervades many modern, popular systems. The Apple Macintosh, for example, presents a scrollable alphabetic display of files for selection within its applications. If file use is a recurrent system (which it probably is), then structuring file lists by temporal recency could give quicker selection, especially with large file stores.

The previous chapter has shown that saving duplicates in their original position is an extremely poor predictive strategy for maintaining lists. Yet it is used by several history systems. It is the only method of reviewing cards visited in Hypercard, and is a presentation option in *wmw* (Section 4.1). Different strategies should be encouraged.

Ordering lists by frequency of use may or may not give any benefit over recency. Although used fruitfully by the dynamic menu system (Greenberg and Witten, 1985), the usability and predictive power of that system could perhaps increase if recent selections were treated preferentially, perhaps by giving them their own display space on the top-level menu screen.

Predicting commands without their arguments has little value. Although predictability is increased, the overall quality of prediction drops because mostly short sequences are offered. Perhaps inclusion of command-sensitive sublists could improve this fault.

When using history, users continually recall the same activities. UNIX *csh* users generally employ history for recalling the same events within a login session. Once an event has been recalled, it should somehow be given precedence.

Functionally powerful history mechanisms in glass teletypes do poorly. UNIX *csh* history fails on two points, even though it is functionally powerful. First, most people (especially novices and non-programmers) never use it. Second, those who do, use it seldom. Only a fraction of all recurrences are recalled through history.

7.2 Corroboration

The general principles of the previous section are based on the UNIX findings. There is no guarantee that they generalize to all recurrent systems and applications. It is useful to see if studies of other systems would produce the same results.

Data on a functional programming language called GLIDE was made available to the researcher after completion of the UNIX study. Since the principles of the previous section had already been elucidated, the GLIDE analysis is a *post hoc* study. The first part of the section briefly introduces GLIDE and describes the data collection method and the subjects. The second part lists the analysis performed and gives the results.

7.2.1 The Glide Study

A brief description of Glide. GLIDE is an exploratory functional programming environment, supporting a lazy functional language, also called GLIDE (Toyn and Runciman, 1988). GLIDE programs consist of a collection of definitions and an expression to be evaluated. Definitions are partitioned into sets called flocks. GLIDE is built upon UNIX and exploits the UNIX file system, definitions being files, flocks directories. UNIX commands are accessible from the GLIDE environment, by

glide> Edit member	*The function definition (not shown) is created and edited in a* UNIX *file called member.g. Member checks if an element (its first argument) is contained in a list (its second argument). The appropriate boolean value is returned.*
glide> Define t1 ← [1.2.3.5.6]	*A definition called t1 comprising a list is created*
glide> !cat member.g	*The user reviews the definition of member*
glide> member 8 t1	*Is 8 a member of t1?*
False	
glide> member 2 t1	*Is 2 a member of t1?*
True	

Table 7.2: A simple Glide dialog

using the *Shell* command or '!', consistent with other UNIX-based tools. Although definitions can be composed directly in the GLIDE environment, they are usually created, maintained and imported through a standard UNIX editor. The command set in GLIDE is relatively small: 23 commands in total at the time of data collection (Finlay, in preparation).

Table 7.2 gives a mythical and self-explanatory extract of an example GLIDE transcript. GLIDE prompts are bold-face, and comments are distinguished by italics.

Subjects and subject use. GLIDE is used to teach functional programming to Computer Science undergraduates at the University of York, and is also used by staff and graduate students in the course of their research. GLIDE usage by 80 such real users was logged unobtrusively over a three-month period for the purpose of studying the nature of expertise (Finlay, in preparation). For the present study, 20 students and staff members having large logs were selected from the 80 participants.

Data collection. The original data consisted of the complete transcripts of GLIDE sessions, including commands issued by the user, the system's response, the function definitions imported from the editors, and a time stamp of the activity (second method→ §2.2.1). The data was reduced for our analysis by stripping all information except for user input lines. These lines were further manipulated by removing the ones containing obvious errors, in particular mis-spellings of commands, incorrect recall of definitions, and syntactical misuse of commands. The final form of a single subject's data is a data file containing his input lines in time-sequence order. The average data file contained 615 input lines, although there is much variation ($std\ dev = 492.2$).

Analysis. The analysis was similar to the UNIX one described in Chapters 5 and 6, although not nearly as extensive. The recurrence rate $\mathcal{R}$ is found and the probability distribution of recurrences for several conditioning techniques are detailed. These are sequential ordering by recency with duplicates in place and duplicates pruned, frequency ordering, and a hierarchy of command lines with command-sensitive sublists. The metrics $\mathcal{R}_d$, $\mathcal{R}_D$, M_d and M_D are calculated over each distribution.

7.2.2 Results and discussion

The average recurrence rate $\mathcal{R}$ is 50.2% with a standard deviation of 11.1%. Extremes range from 34% to 71.1%. The average length of a GLIDE input line is 12.6 characters, where terminating line feeds are not counted and duplicate lines are included. The average length of submissions that already exist on the history list is 9.7 characters, while those that appear for the first time are 15.5 characters long. The maximum possible value for M_D is therefore $\mathcal{R} \times 9.7/100$, which is 4.87 characters.

Table 7.3 summarizes the results for selected conditioning methods, where each row presents the values of the various metrics over the last fifty items on the history list. Figure 7.1 graphs the metric $\mathcal{R}_D$ on the vertical axis; the horizontal axis shows the position of the repeated GLIDE command line on the history list relative to the current one. Figure 7.2 is similar, except that the vertical axis now represents M_D (*cf* Figures 6.1 and 6.2).

The results are quite similar to the ones found in the UNIX study. The most glaring difference is the lower recurrence rate (50% versus 75%). Part of this difference could arise from the fact that arguments in GLIDE functions are lists. Since lists are generally not as persistent as filenames, arguments (and their lines) would not recur as often. Another part of this difference could be an artifact in data collection, for white space and errors are handled differently. First, although all unimportant white space was removed by *csh* in the UNIX study, this was not done for GLIDE. Recurrences arising from two semantically identical lines with syntactically different white spaces are not counted as a repeating submission. Second, errors in the UNIX study were marked when a *csh* error message was produced. GLIDE had no such capability, and most semantic errors were not tagged, although quite a few syntactic ones were removed manually. Since errors are generally not repeated, the number of unique lines is overestimated. Still, these artifacts are not expected to change the value of $\mathcal{R}$ greatly[1].

When conditioning methods are contrasted for GLIDE, they follow the same rank ordering as that produced by *csh* use. Although there are fewer recurrences with GLIDE, the predictive power of the conditioning methods is relatively greater. For example, up to 43% of all user activity can be successfully predicted with working sets of ten predictions. Given that $\mathcal{R} = 50\%$, which is the best a perfect reuse facility could do, the best predictive method is 85% effective for GLIDE recurrences

[1] The recurrence rate calculated over GLIDE logs including errors is 48.6%, just a few points lower than the logs with errors removed manually.

Conditioning method	Distance 1	2	3	4	5	6	7	8	9	10	20	30	40	50
Probabilities of a recurrence at the given distance d in percent ($\mathcal{R}_d$)														
Recency, duplicates saved:	5.74	13.00	6.25	4.12	2.55	1.71	1.30	1.10	0.83	0.68	0.33	0.13	0.10	0.09
Recency, duplicates pruned:	5.74	13.41	7.15	4.40	2.77	1.77	1.54	1.14	1.03	0.74	0.25	0.18	0.04	0.03
Frequency order:	7.28	4.30	3.1	2.95	2.45	2.08	1.76	1.71	1.61	1.36	0.52	0.44	0.21	0.13
Command hierarchy:	5.74	15.69	8.34	4.87	2.85	1.80	1.35	1.19	0.87	0.61	0.23	0.17	0.03	0.01
Accumulated probabilities of a recurrence up to a given distance d in percent ($\mathcal{R}_D$)														
Recency, duplicates saved:	5.74	18.74	24.99	29.11	31.66	33.37	34.67	35.78	36.61	37.29	41.44	43.54	44.76	45.62
Recency, duplicates pruned:	5.74	19.15	26.30	30.70	33.47	35.24	36.78	37.92	38.94	39.69	43.54	45.58	46.72	47.43
Frequency order:	7.28	11.58	14.68	17.63	20.08	22.17	23.93	25.64	27.25	28.61	37.11	41.52	43.97	45.34
Command hierarchy:	5.74	21.43	29.77	34.63	37.48	39.28	40.63	41.82	42.68	43.30	46.49	47.97	48.74	49.08
The average number of characters saved over all subjects per recurrence at a given distance ($\bar{c}_d$)														
Recency, duplicates saved:	8.16	10.22	10.41	10.80	10.97	8.53	9.80	8.97	7.65	8.18	5.97	5.07	3.23	4.16
Recency, duplicates pruned:	8.16	10.20	10.59	10.60	10.20	9.42	9.11	9.09	7.76	6.94	6.08	3.59	2.11	1.30
Frequency order:	6.49	8.29	8.63	8.35	8.78	10.32	10.11	10.61	9.81	9.90	7.83	7.84	5.19	5.31
Command hierarchy:	8.16	10.65	10.61	10.33	9.97	9.38	8.36	9.00	7.59	8.23	6.50	3.91	1.73	1.35
Cumulative average savings in characters of D predictions over all submissions (M_D)														
Recency, duplicates saved:	0.47	1.88	2.53	2.98	3.26	3.42	3.55	3.66	3.74	3.81	4.17	4.38	4.48	4.55
Recency, duplicates pruned:	0.47	1.92	2.69	3.16	3.44	3.62	3.78	3.89	3.98	4.03	4.38	4.55	4.64	4.70
Frequency order:	0.47	0.84	1.11	1.37	1.59	1.81	1.99	2.18	2.36	2.50	3.46	3.97	4.23	4.39
Command hierarchy:	0.47	2.18	3.07	3.57	3.86	4.03	4.15	4.27	4.34	4.40	4.67	4.78	4.84	4.86

Recurrence rate $\mathcal{R}$ is 50.24%

Maximum value of M_D is 4.89 characters

Table 7.3: Evaluating various conditioning methods in Glide

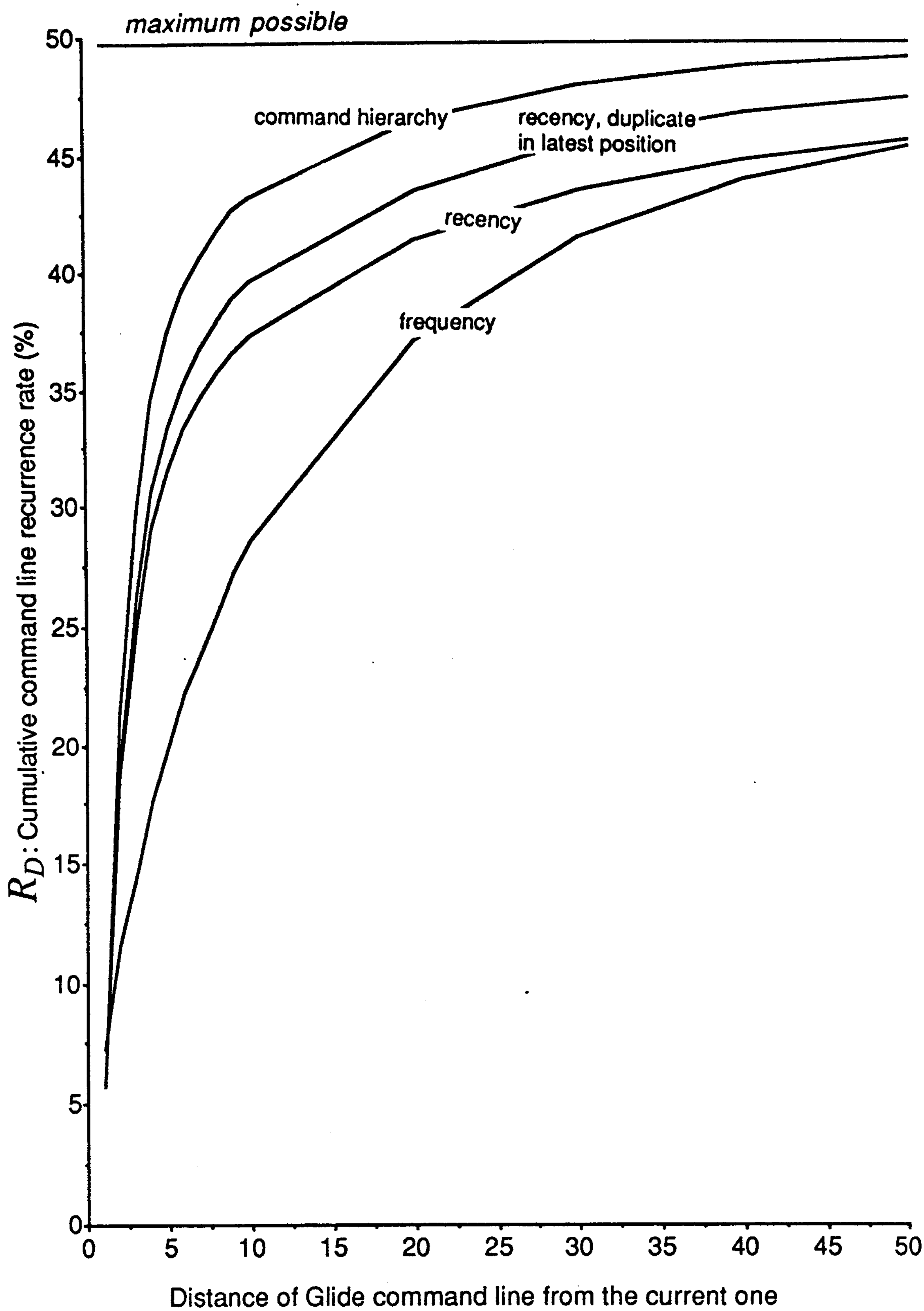


Figure 7.1: Cumulative probabilities of a recurrence over distance for various conditioning methods

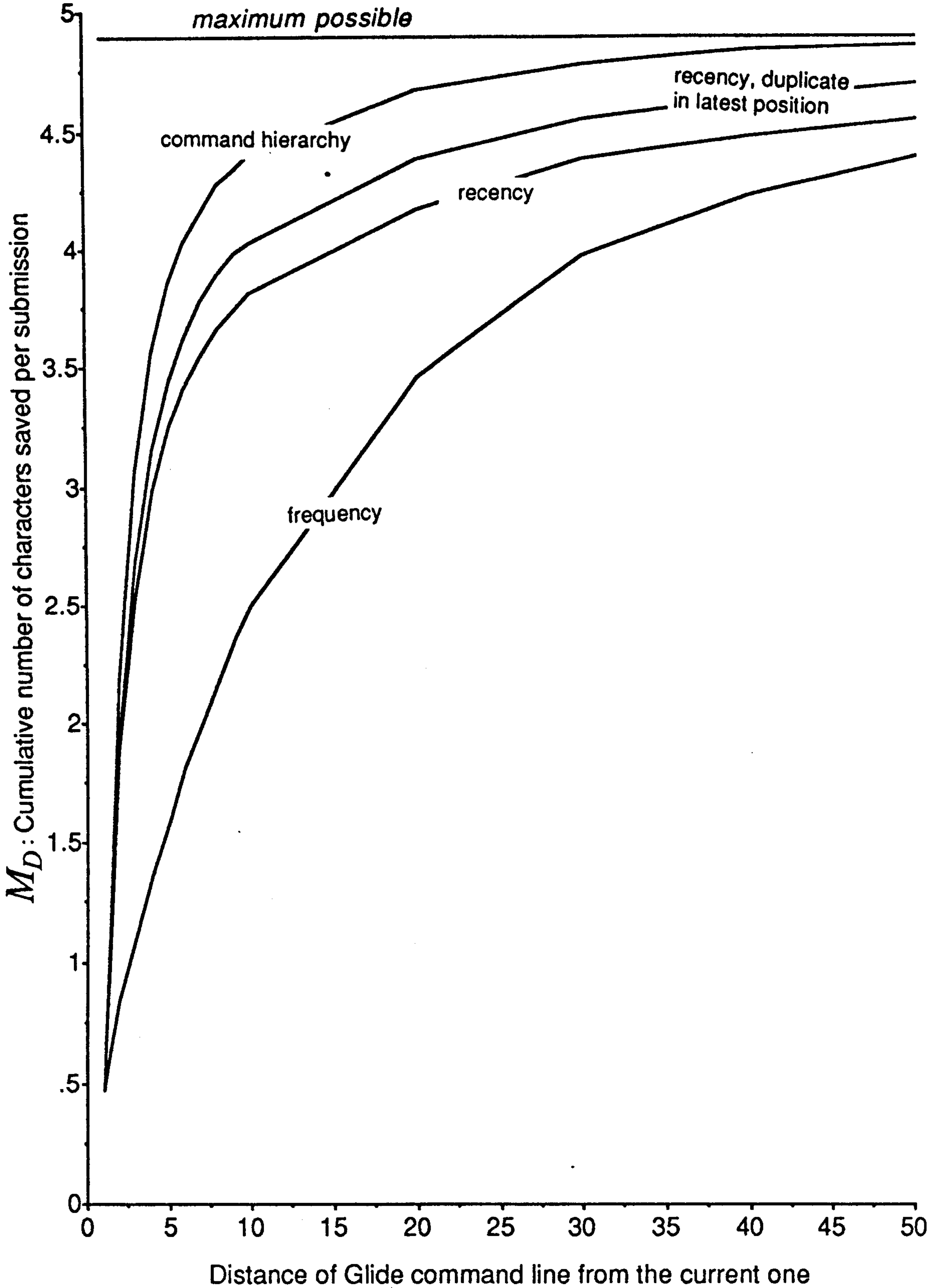


Figure 7.2: Cumulative average number of characters saved per submission over distance

(*cf* 75% for UNIX). When the quality metric is incorporated, up to 4.43 characters are submitted per submission when 10 predictions are available. Since the maximum value of M_D is 4.87 characters, the best method is about 90% effective (*cf* 75% for UNIX).

In summary, despite the numeric differences in the analyses, the principles developed from the UNIX study are corroborated by subjecting GLIDE to the same analysis. Although new activities are composed regularly by users (around 50%), a substantial portion of their activities are repeated (50%). Users exhibit considerable recency in activity reuse in the same way as UNIX. The major contributions are provided by the previous 7 ± 3 submissions, and the second to last command line recurs more often than any other input (Table 7.3). Although some user activities still remain outside a small working set containing the recent submissions, the predictive power of these sets can be improved by suitable conditioning. Command-sensitive sublists are particularly effective.

7.3 Stepping back

The analysis made of the computer systems studied so far views an activity as a single independent command line. From a purely statistical standpoint, interfaces that simplify reuse of particular lines have potential to reduce certain tedious aspects of everyday human-computer interaction. But are activities really independent? Could sets of activities, for example, be grouped as reusable and perhaps more effective goal-specific scripts or plans? This section steps back from the empirical findings gleaned through observations to a broader view of reuse.

7.3.1 Plans and situated actions

A major design premise of some user support tools, particularly in the office environment, is the belief that a worker's activity follows preconceived plans and procedures[2]. This views

> ...the organization and significance of actions as derived from plans, which are prerequisite to and prescribe action at whatever level of detail one might imagine. Intentions are realized as plans-for-actions that directly guide behaviour, and plans are actually prescriptions or instructions for actions. These plans reduce to a detailed set of instructions (which may also be sub-plans) that actually serve as the program that controls the action.
>
> — paraphrased from Suchman, 1980

If the premise of pre-conceived plans is indeed true, then reuse facilities could be replaced by planning tools. One example of such a tool is OSL, a high-level office specification language (Kunin, 1980). It allows one to describe algorithms that capture rationalized goal-related office procedures. Programming by example is another possibility. These systems allow people to encapsulate activities as a structured well-defined procedure→ §4.3.

The procedure could be designed and used immediately, and would be available for reuse any time thereafter. Reuse facilities, on the other hand, would be useful only after the user starts executing the details of a plan.

But recent work by anthropologist Lucy Suchman disputes the notion of preconceived plans. Her thesis treats plans as derived from ***situated action*** — the

[2]An argument parallel to the one in this section was developed independently by Lee (1988a).

necessarily *ad hoc* responses to the actions of others and to the contingencies of particular situations.

> The course of action depends in essential ways upon the action's circumstances. Even casual observation of purposeful action indicates that, as common sense formulations of intent, plans are inherently vague as they are designed to accommodate the unforeseeable contingencies of actual situations of action. For situated action, the vagueness of plans is not a fault but, on the contrary, ideally suited to the fact that the detail of intent and action must be contingent on the circumstantial and interactional particulars of actual situations.
>
> — paraphrased from Suchman, 1980

Suchman suggests that: 1) plans are *post hoc* rationalizations of actions *in situ*; and 2) in the course of situated action, deliberation arises when otherwise transparent activity becomes in some way problematic.

But where does our belief in plans come from? According to Suchman, our descriptions of actions as purposeful come always before or after the fact, in the form of envisioned projections and recollected reconstructions.

> We can always perform a *post hoc* analysis of situated action that will make it appear to have followed a rational plan, for rationality anticipates action before the fact, and reconstructs it afterwards. Only after we encounter some state of affairs that we find to be desirable do we identify that state as the goal toward which our previous actions, in retrospect, were directed all along.
>
> — paraphrased from Suchman, 1980

Assuming that user activity on computers does follow situated actions, then reuse facilities are more viable than planning systems. Since reuse facilities allow one to select, possibly modify, and redo single actions, they respond well to the circumstances of a situation. When previous actions are collected as goal-related scripts of events, this flexibility is lost.

7.3.2 Recurrences: natural fact or artifact?

Where do recurrences come from? Are they naturally part of a human-computer dialog or are they artifacts imposed by poorly-designed interfaces? If the former, then reuse facilities are an essential component of a good interface. If the latter, they are merely add-on patches; the interface itself should be reconsidered. We will see that, depending upon the situation, recurrences can be either.

The recency effect seen in recurrent systems is probably due to repetitive actions responding to interactional particulars of a situation that is changing only slightly. In a development task, for example, the situation may be debugging, where the usual responses to particular circumstances comprise a debug cycle. When the development is complete, the cycle terminates. Debug cycles are seen throughout the UNIX traces, and seem responsible for the recurrence probability peaking on the second to last submission. Consider this typical trace excerpt from a non-programmer developing a document.

```
nroff Heading2 Chapter1 | more
emacs Chapter 1
nroff Heading2 Chapter1 | more
emacs Chapter 1
nroff Heading2 Chapter1 | more
emacs Chapter 1
nroff Heading2 Chapter1 | more
emacs Chapter 1
nroff Heading2 Chapter1 | lpr -Plq &
...
```

The sequence shows the user developing a document by iteratively editing the source text and evaluating the formatted result on the screen, using the *emacs* editor and the *nroff* typesetter. The user's evaluation of the situation determines how often the cycle is repeated. When she was satisfied with the document, she terminated the cycle by producing a final hardcopy.

Another extracted and slightly simplified sequence from a different user illustrates program development using the *fred* editor and the ada compiler.

```
fred
ada -M concur -o q5.o q5.a  | repeats 11 times

q5.o                        | repeats 3 times

fred
ada -M concur -o q5.o q5.a  | repeats 6 times
q5.o
```

This shows three debug cycles all related to the same development process. In the first, the user edits some source code until it successfully compiles (11 cycles), and then evaluates the executable program. Final tuning of the program is done by expanding the initial debug cycle to include editing, compilation, and execution.

The actual development cycles seen supports Suchman's thesis of situated actions. The user's plan for the development process is necessarily vague, since bugs and difficulties cannot be predicted beforehand. The developer must, of necessity, respond to the particulars of each individual situation. These responses appear repetitious because the situation is altered only slightly after each action[3].

In the case of debug cycles, it is certain that some recurrences are artifacts that can be eliminated through different interfaces. Interpreted or incrementally compiled programming environments, for example, remove the necessity for repeated recompilation of the source (see Reiss, 1984, for an example). In other domains, what-you-see-is-what-you-get text processors and spreadsheets not only remove the "compile" step from the cycle, but also show the current state of execution. No

[3] Although repetitions in the UNIX dialog shown appears identical, the changes made within the editor application are not repetitious.

distinction is made between the source and developing product, and any changes update the display immediately.

But other recurrences are not so easily eliminated. Repetitions are often a natural part of the task being pursued. Design work, for example, is fundamentally an iterative process. A second example is telephone dialing. The caller may dial the same number repeatedly when a connection is not made, or he may be a middleman arbitrating information between two or more other people. Retrieval of information in manuals is another example of recurrences that arise from repetition of our intentions rather than from interface artifacts. Or consider navigation on computers where people must locate and traverse the many structures necessary for their current context (*eg* navigating file hierarchies and menu-based command sets, and manipulating windows to find pertinent views). Since context switching is common, these traversals would recur regularly.

Other recurrences come from long-term context switching. In the UNIX traces, it is usual to see work on a particular task (say document development) occurring in bursts. In a single login session, these bursts may be just a single task interrupted by other dependent or independent diversions. Over multiple login sessions, tasks are constantly released and resumed.

In summary, some recurrences are artifacts arising from particular aspects of a system design and implementation. Others are not, for they arise directly from the user's intention, independent of the computer system. Perhaps future systems will minimize the need for reuse facilities by eliminating the artifacts. For the present, reuse facilities remain a potentially viable and very general way of handling repetition.

Concluding Remarks

A set of empirically-based principles of how people repeat their activities on computers was listed in this chapter. These principles were reformulated as general design guidelines for the design of reuse facilities. Although there is no guarantee that the principles apply to all recurrent systems and applications, they were supported by a *post hoc* analysis of usage transcripts of the GLIDE functional programming language. The chapter also discussed whether it is appropriate to treat activities as single, independent entities. It was argued that the course of action is a response to the current situation. As a consequence, single activities could more readily respond to changing situations than a preconceived plan. Finally, it was argued that recurrences are both natural fact arising from cognitive behaviour and task requirements, and artifact arising from poor interface design.

The appeal of a reuse facility is its potential benefit for any application dialog classified as a recurrent system. A reuse facility only requires that submissions entered to the application can be collected, presented, and selected for reuse. Since no semantic knowledge of the domain is needed, it is a general turnkey approach.

Chapter 8

Organizing Activities Through Workspaces

> In every trade a specific way of organizing tools and objects for the craftsman has been established. Every workshop is equipped with appropriate tools and organized with respect to the specific working situation. In this way strategies for the solution of typical problems are at hand for the workers.
>
> — Dzida, Hoffmann and Valder, 1986

This thesis opened by advocating the common metaphor of tools for thinking about command-based systems, where command lines are the tools that manipulate the materials in one's environment. The four preceding chapters pursued the notion that recently used lines, like tools, should be available for reuse. But reuse is not the only strategy for supporting user activities. It is evident that people impose some organization on their computer tools and materials, just as craftsmen do with their physical counterparts. Real workshops support these organizations through toolboxes for arranging and locating tools, workbenches for performing specific tasks, shelving and drawers for keeping relevant tools and materials readily available, and so on. Computing environments, on the other hand, do little to promote personal organization. A command-based interface is comparable to an unhelpful clerk who waits for you to name the tool you want, retrieves the tool (if available) from a separate room, and demands that you return it immediately after use. At the other extreme, arranging facilities into fixed taxonomic menus is reminiscent of a totalitarian chaining of tools to a single location.

One theme of this dissertation is that people mentally structure their activities on computers, and that a software tool can be embedded into the interface to support these implicit organizations. Section 8.1 reviews evidence that people's activities are loosely related by tasks and by functionality, and can be grouped accordingly. In particular, a user's normal computer interaction can be partitioned into interleaved sets of goal-related tasks. The next section follows with several relevant implications leading to design suggestions for a *workspace* — an interactive software tool that collects together and makes available a user's related materials in one convenient location. Finally, a few existing implementations that profess to support user organization are described to give the reader a feel for what is currently available.

8.1 Relating activities

Activities are not necessarily independent of each other, but may be related in many ways. In particular, users partition their actions and the objects they manipulate (such as files) into sets of goal-related tasks, called a ***task set***. This was first articulated by Bannon *et al* (1983), who analysed command line activity on a UNIX system by asking users to annotate their command histories periodically with their intentions. Their method and a short sample annotated trace were detailed previously in Section 2.2.2.

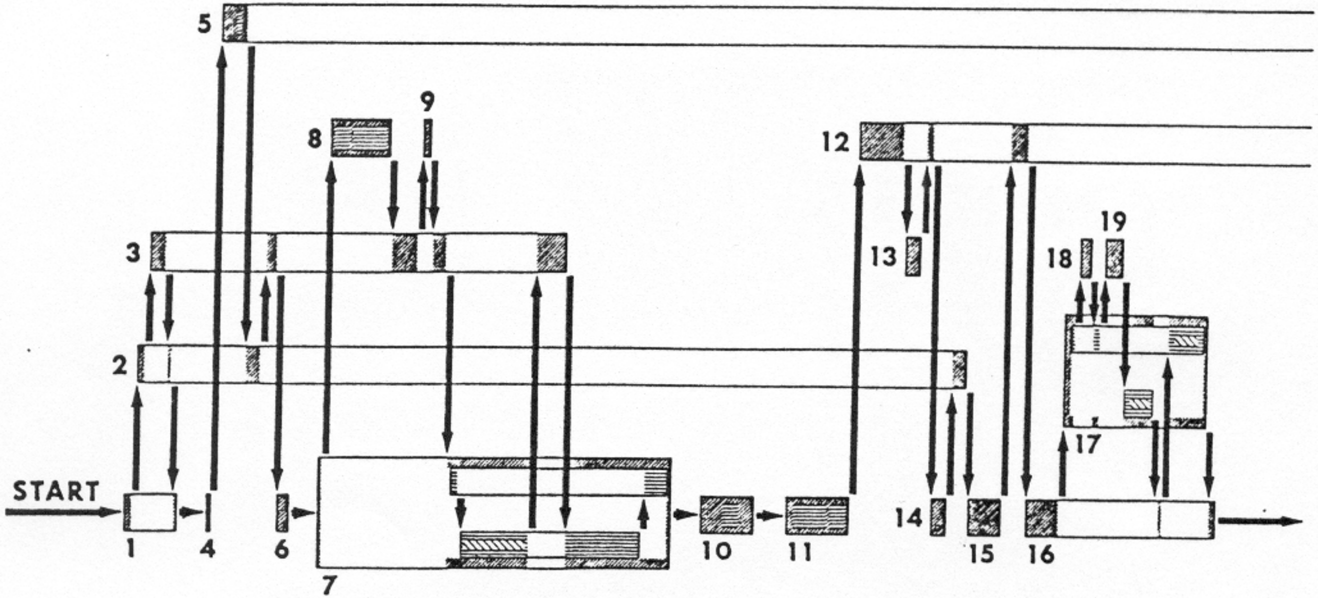
To illustrate the idea of a task set, consider the case of one non-programmer

A user's task set for preparing a specific document	
Command line	**Meaning**
cd ~/Thesis	*go to the directory containing the desired file*
emacs Chapter1	*edit the file*
spell Chapter1 | more	*list the spelling mistakes in the file*
nroff Heading Chapter1 | more	*view the formatted file on the screen*
nroff Heading Chapter1 | lpr &	*produce a hardcopy of the document on the standard printer*
nroff Heading Chapter1 | lpr –Pci &	*produce a hardcopy of the document on the printer named "ci"*
rm *.BAK	*remove the backup files created by the editor*

Table 8.1: A user's task set for preparing a specific document

from the current study preparing a document (a thesis chapter). A review of her trace revealed that several command lines, listed in Table 8.1, were used consistently for this purpose. These lines did not always follow in the same order. The activity selected at any moment from the task set seemed to depend on the particular circumstances (see Section 7.3).

Tasks are not invoked sequentially, but are interleaved because the user switches, suspends and resumes his goals. This is graphically illustrated by Cypher's analysis (1986) of the activity flow during one person's computer use for a single morning, reproduced in Figure 8.1. His analysis was based on the annotated history records collected by Bannon *et al* (1983). The boxes and sub-boxes in the Figure represent the duration of the 19 main activities observed and their further sub-activities. The user's progression through and between tasks is followed by the arrows, while activity performance is illustrated by the shaded areas. Annotations at the bottom describe the task. For example, the session starts with *read mail*, switches to *reposition window*, switches to *msg conversation*, and so on (Cypher, 1986). Each task shown may, of course, be made up of one or more activities.



1 Read mail
2 Reposition window
3 Msg conversation
4 Check reminders
5 Arrange a meeting
  Check calendar
6 Delete old messages
7 Respond to P's message
  Send a reply
  Set up a new account
    Log in to remote computer
8 Help A
  Find note about "fmt"
  Try it out
9 Delete outdated message
10 Mail from Y
  Find history programs
11 Fix the clock
  Read documentation
  Ask for help
12 Read over printouts
13 Look at a note
14 Play with windows
15 Read new mail
16 Make a note
17 Save it as a good example
  File it
    Find the sub-bin
  Describe the example
    Locate the text
18 Retitle a note
19 Make a main bin

Figure 8.1: A user's flow of activities for one morning's computer use, from Figure 12.1 in Cypher, 1986

Further evidence that users interleave task sets is provided by studies of window systems. Although all activity pertaining to a particular task is often confined to a single window, this is not necessarily the case. For example, the contents of multiple windows could be a different software representation of the same task. Or windows could be implicitly related by the information in one being accessed (and perhaps combined with) another (Card *et al*, 1984; Greenberg *et al*, 1986). Card *et al* (1984) recorded how a user selected windows and suggested that the patterns observed are reminiscent of the locality of reference behaviour when paging virtual memory (Denning, 1970). Most user activity revolves around frequent references to a small set of windows, and a window "fault" often signals a transition to another small set of windows (Card *et al*, 1984). These findings of Bannon *et al* (1984), Cypher (1986), and Card *et al* (1984) suggest that task switching occurs at many levels: between sequences of input lines; between particular windows on a screen; and between sets of windows.

These studies do not show how task sets differ between users. Perhaps a clue can be gleaned from the work of Nielsen *et al* (1986), who investigated integrated software usage by professionals in a work environment. The main goals, subgoals, and methods used for satisfying the goals were identified for each professional. Data was collected through questionnaires and interviews. Results were as follows.

- Five high-level application programs accounted for 42% of program use over the population.

- It was not possible to rank the programs accounting for the other 58% at the population level, as most were used by only a few professionals each.

- Integrated packages were not exploited fully. For example, users chose non-integrated modules if they were judged more effective in terms of goal achievement than the integrated version. In other words, users were "choosing a set of heterogeneous programs and integrating them in their own way" (Nielsen *et al*, 1986).

Nielsen *et al* conclude that integrated programs are not a panacea for communicating with general purpose computers, for "most current analyses have not yet developed categories of representation adequate for identifying the task requirements of integration" (p167). Even so, the large number of different programs used by professionals and the different ways they were "integrated in their own way" suggests that there are both subtle and overt differences between the task sets of users.

Activities are also categorized according to the function they serve, rather than the particular task they address. By way of analogy, consider a mechanic's functionally-arranged toolbox, where screwdrivers are located in one compartment, wrenches and sockets in a second, electrical equipment in a third, and so on. Although particular tools may be selected and placed on a workbench for a specific job (*ie* a task set of tools), the functional arrangement gives a good general organization. Functional organization is also possible in computers. For example, Hanson *et al* (1984) classified UNIX commands into five general categories and measured their frequency of use[1]. The categories are generic editing commands that shape text and other objects (36%), orienting commands that inform users about their working environment (21%), process management commands used to integrate individual commands into more complex units (10%), and social commands that allow people to exchange information with each other (3%). The remaining 30% were task-specific commands. Individuals would, of course, have their own different classifications.

There are many other ways of organizing activities. Sub-activities can be collected and treated as a single unit (*eg* pipelines, shell scripts). Activities may be categorized not by function but by the object they manipulate (*eg* file-centered). However, it is beyond the scope of this dissertation to discuss further possibilities.

[1]Since the frequency of use was determined by population statistics, it is not clear how accurately they apply to the individual→ §3.5.

In summary, empirical evidence and intuitive insight suggest that activities are related in several ways. First, user activity is partitioned into multiple levels of interleaved task sets related by the user's own particular goals. Different users have different task sets. Second, activities can be associated either by function or by the object being manipulated. Third, sub-activities can by combined into a single chunk. It is self evident that users organize their activities in many (perhaps vague) ways throughout the computer dialog. The only truly surprising thing is the dearth of computer support for this kind of organizing activity.

8.2 Implications: suggestions for workspaces

While people organize their activities on computers, many systems either do not make these organizations explicit, or do so in very restricted ways. Without online support, people must recall or reconstruct through memory the previously established set of activities, or they must use existing, perhaps inappropriate, groupings. And users cannot easily share groupings that could be mutually beneficial.

This dissertation argues that the organization of activities should be made explicit and available for use through a software tool generically called a *workspace*. Through a workspace, users are able to collect, organize and use their online materials, and switch between tasks. When combined with a reuse facility, users can not only select items that were recently entered, but could bring in activities recorded in the more distant past.

Although not new, the notion of a workspace is not as prevalent in the literature as might be expected. This section starts by surveying the few existing works of researchers who derived workspaces from empirical analyses. Suggestions for workspaces identified in these reports are reviewed. Additional suggestions believed to be important are described later.

8.2.1 A review of suggestions

The concept of a workspace has been proposed by other researchers, although the labels given to the work sometimes differ (*eg* workbenches, tool bins, tool instruments). Each researcher seems to have his own reasons for recommending a strong explicit organization of user activities. The evidence is usually intuitive, rather than experimentally supported.

For example, Norman (1984a, 1984b) identifies four stages of user activity — intention, selection, execution, and evaluation — each requiring different interface support strategies. He suggests that "workbenches that collect together relevant files and software support in one convenient location" can enhance user activity in some of the stages noted above (Norman, 1984b, p368). The visibility of these items provides information that aids both the formation of the intention and its selection. If items are arranged properly within the workbench, selected items can then be easily executed. Unfortunately, Norman does not elaborate further on his workbench idea.

Another example of a workspace recommendation comes from Nakatani and Rohrlich (1983), who describe a three-layer system of organizing collections of "soft machines" into a *tools* structure. A "soft machines" metaphor graphically realizes special-purpose machine-like interface for certain activities. They suggest that this scheme may fail if the collection of machines is not somehow organized. "We want the collection organized so that we have easy access to all the machines needed for the project with no unneeded machines cluttering our work environment" (Nakatani and Rohrlich, 1983 p23). They propose a method of integrating links between soft machines by using the analogy of tools in a workshop. The hierarchy used is a *tool bin* (which is the entire set of tools); a *workshop* (which collects similar tools); and a *workbench* (on which the actual work is done). Although they also suggest that this hierarchy should have a parallel *data* hierarchy, they do not elaborate any further.

The most comprehensive work to date is that of Bannon *et al* (1983). Building on their work describing interleaved task sets, they propose an environment that allows users to arrange activities so that their goals and sub-goals are easily achieved (Bannon *et al*, 1983). They suggest several guidelines.

1. Reduce a user's mental load when switching tasks.
2. Support suspension and resumption of activities.
3. Maintain records of activities.
4. Allow functional groupings of activities.
5. Provide multiple perspectives on the work environment.
6. Allow interdependencies among items in different workspaces.

As tasks are frequently suspended and resumed, users should be able to navigate easily between activities (points 1 and 2 above). This was further elaborated by Card and Henderson (1987), who add the following to the wish list.

7. Task switching should be fast.
8. Task resumption should be fast.
9. It should be easy to re-acquire one's mental task context.

Workspaces can act as visible place-holders to reduce one's mental load. They should save and restore the task state between excursions. Also, the amount of cognitive overhead when switching tasks should be reduced by allowing the user to jot down notes and attach them to particular workspaces.

Users may wish to repeat an action identical or similar to one invoked recently (point 3), a major argument of this dissertation. Bannon *et al* (1983) suggest that re-usable context-sensitive records of activity should be included within the workspace.

The obvious function of a workspace is to group activities (point 4). These relationships should be defined by the user, as discussed in the next section.

Workspaces are not necessarily independent of one another, and relationships between them should be supported (points 5 and 6). Multiple instances of particular items should be allowed, as items from one workspace can be useful in another. Information in one workspace may be important and/or related to another, and the display should make inter-relations obvious. Items should be collectively shared among several tasks, and their presentation should be task-specific (Card and Henderson, 1987).

8.2.2 Additional workspace suggestions

The suggestions above, although important, are confined to support for task switching. The discussion below supplements the list of design suggestions that should be fulfilled by workspaces. It emphasises the role of symbols, end-user personalization, and building structures by collecting previous — instead of anticipated — activities.

Abstracting activities through symbols. Although primitive activities (such as UNIX command lines) must be recorded in a workspace if they are to be reused, they need not be presented to the user in their native form. Instead, syntactic computer actions can be abstracted as symbols known to the user, where these symbols remind users of the meaning behind the action[2]. The expected effect is to minimize the user's need to translate his desire into the syntactic actions of the system by providing him with his own meaningful language (Shneiderman and Mayer, 1979; Perlman, 1984).

[2]I use the term "symbol" according to its dictionary meaning: "a thing generally regarded as typifying, representing, or recalling something" (Oxford Dictionary of Current English, 1984). Other researchers have different definitions. Perlman, for example, describes a symbol as a letter representing a name, which in turn represents a concept (Perlman, 1984). The symbols here are not necessarily simple letters, but may be any textual or graphical representation of an activity.

When symbols are both visible and selectable, they can be much more useful than the conventional abbreviations provided by most command-based systems. For example, a symbol might be a mouse-sensitive item selected from a menu, panel or iconic display. When selected, the underlying action is executed. There is no need for the user to have to recall the name of the symbol or the syntax of the action invoked.

Symbols are, of course, not new to computer systems. What is novel is how they can be used within a set of workspaces to bring together related activities. A collection of symbols may represent the activities that make up a task set or functional grouping. The collection may be further abstracted as a symbol, which can itself be included in other collections. The desired effect is to represent a task set as a collection, and to provide links from one task to another. This supports interdependencies between workspaces. The user either executes particular activities within one workspace or calls up related workspaces by selecting the appropriate symbol. Multiple instances of workspaces are supported as well, since links need not be exclusive.

Symbols can also represent other attributes associated with an activity. Each entry can be annotated with extra information such as help text or a property sheet. Depending on how one selects the symbol, the activity may be executed, the help text displayed, or a property sheet raised for further clarification.

End user personalization. Who actually builds and maintains workspaces — the overall structure, the activities included, and the symbols chosen? From the population perspective, designers can create default workspaces that are adapted by users to pursue common task sets. Previous chapters, however, argued that little activity overlap exists between individuals, implying the need for some level of personalization. Ideally, when a need arises that is not addressed well by the pre-defined workspaces, each user may immediately: a) add, modify or delete any elements within a given workspace: b) create new workspaces or destroy old ones; and c) alter the way workspaces are linked together. This capability is called "end-user personalization".

End-user personalization should allow individuals, including non-programmers, to easily choose and arrange the tools and materials in their workspace. This requirement is vital, for designers can rarely predict user activity. Personal groupings exist (Sections 3.3 and 8.1). Particular users have their own unique task sets, and no universal scheme can cater to individual idiosyncracies. Furthermore, user needs, tasks, and preferences change over time, and so workbenches should be easily modifiable.

Using old activities to construct workspaces. Users will not use a personalized workspace facility if it involves a significant overhead. The interface must therefore minimize the mechanical overhead of managing workspaces. More important is the cognitive overhead of forming activities collected by a workspace. If users must anticipate what they are going to do, then the burden of collecting the appropriate materials into the workspace will be high. People may not know precisely what activities are required for their task (→ §7.3). Even when they do, the activity desired must be composed, debugged, and tested to make sure that it will perform correctly. A better method would have users collecting together their previous activities.

It was argued in Chapters 4 through 7 that people repeat their activities, and that a reuse facility has an important role in the human-computer interface. By merging this facility with a personalized workspace, and by making old activities also available as workspace items, considerable power can be gained. Users would not only be able to redo old actions but they could use the history list as the primary source of tried and tested candidates for their collections. They could select, copy and add them directly into their workspace. I believe this novel synthesis is a major contribution of this thesis, since the potential benefits are so important. First, workspace items do not have to be anticipated. Instead, users can perform their task as normal and decide at any time to assemble the relevant previous activities that make up the task set. Second, since these items are directly available, they are recalled rather than composed. Third, they have already been debugged and tested to some extent. Finally, interaction tedium is minimized, since modern techniques used for selecting and transferring activities (the cut/copy/paste metaphor) should take no more than a few seconds of time.

In summary, a workspace should allow a user to collect together and abstract through symbols both new and previously entered activities into meaningful collections.

8.3 Implementations

Organizational strategies are not new to computer systems. Many top-level interfaces, for example, provide hierarchical directories for arranging files. Directories in common are pre-arranged by the system designer. Individual needs are also recognized — users may arrange their particular sub-tree of the hierarchy in any way they please.

Similarly, certain interfaces allow related actions to be grouped explicitly. Dedicated function keys are often arranged in clusters (*eg* cursor movement and editing actions). Attributes of objects may be listed and manipulated within property sheets (Witten and Greenberg, 1985). Hierarchical menus provide a hard-wired grouping of actions, where each menu page is dedicated to some pre-defined task (*eg* file manipulation). Products designed to address particular needs bundle selected activities into a single package.

Implementations related to workspaces fall into three broad categories: menu-based taxonomies, object-oriented browsers, and multiple virtual workspaces. Menus group activities — actions and perhaps their manipulated objects — into taxonomic chunks. Browsers, on the other hand, provide a rich development environment strongly tied to the explicit structure inherent in objects produced by object-oriented programs. Multiple virtual workspaces allow users to collect and navigate between screenfuls of windows. The three categories are described in greater detail below, and are illustrated with a few implementations. Table 8.2 summarizes how six contemporary workspace designs fit the suggestions mentioned in the previous section. The list includes *Workbench*, a design described in the next chapter. The intent is not to survey all workspace possibilities, but to give the reader a feel for how some important characteristics have been implemented.

Structuring activities through menus. Taxonomic menus classify a domain hierarchically and allow the user to navigate through it. As he does so, he attempts to focus on the desired information by refining the category that is currently displayed. These menus are familiar to computer users, and have been used to access information in very large databases (*eg* Videotex systems, Godfrey and Chang, 1981), and to organize activities in office automation systems (*eg* IBM *Aoss*).

A command interface to an operating system can be built using the same kind of taxonomic structure. For example, MENUNIX shows how an extensive and flexible operating system interface can be implemented with menus (Perlman, 1984). It allows access to the UNIX system by displaying two menus from which users can make selections: the *file menu* which lists the current working directory, and the *program menu* which lists the programs currently available (Figure 8.2). Command lines composed through these menus can be modified further using a line editor at the bottom of the screen, while previous submissions can be reselected through a small but visible history list.

When a file menu entry is selected, MENUNIX tries to do something sensible

Property	Menunix	Smalltalk	Rooms	Room	WCS	Workbench
			Task switching			
Reduces mental loads when switching tasks	Grouped activities saved in menus	All information retained between tasks	Window-based applications & window attributes saved between tasks	Task activities are saved as icons	Task activities are saved as pop-up menu items	Task activities are saved as drawers in a cabinet
Suspend and resume activities	No	Very slowly through projects	Rapid task switching through doors and Overview screen	Task switching through doors	Each workbench represented in its own window	Can switch and backtrack between drawers; each workbench represented in its own window
Multiple perspectives of the work environment	No	Not really. Each project is independent of the other	Window collections are sharable between workspaces	Not known	Multiple instantiations of the same workbench are possible	Multiple instantiations of workbench are possible
Interdependencies among items	Menu items need not be unique between workbenches	Objects related through hierarchy	A window-based application can appear in any room	Copies of activity icons can be made and used in other rooms	Workbench links and menu items can be shared	Drawer handles allow drawers to be linked and shared
			Grouping activities			
Functional groupings of activities	Yes, as items in a menu	Yes, as methods in an object and objects in a hierarchy	Yes, as collections of window-based application programs in a room	Yes, as activity icons in a room	Yes, as items in several popup menus attached to a workbench	Activities grouped through tool panel, drawers and cabinet
End user personalization of functions	Not expected	Only through programming	Window attributes and their applications are user defined	Icons are acquired through a "supply room" and their attributes can be altered.	All pop-up menu attributes are user defined	All cabinet and tool panel attributes are user defined

Table 8.2: Suggestions implemented by existing workspace designs (continued on next page)

Property	Menunix	Smalltalk	Rooms	Room	WCS	Workbench
Reuse						
Maintain records of activities	Yes	No	No	No	No	Yes, in several ways through an explicit reuse facility
Old activities transferable to workspace groupings	No	No	No	No	No	Yes, through copy and paste
Symbols						
Abstracting activities with symbols	Yes, through descriptions and one-letter symbols	Yes, through class and message categories, objects, and message selectors	Limited. Doors represent rooms	Icons represent activities and doors represent rooms	Yes, with names, popup menu groups, and help messages	Yes, with tool and drawer handle labels and help menus
End user personalization of symbols	No	Through programming only	Rooms and doors can be named	Room maker allows rooms to be defined	Names, activities and help messages are user defined	Names, activites and help messages are user defined

Table 8.2: Suggestions implemented by existing workspace designs (continued from previous page)

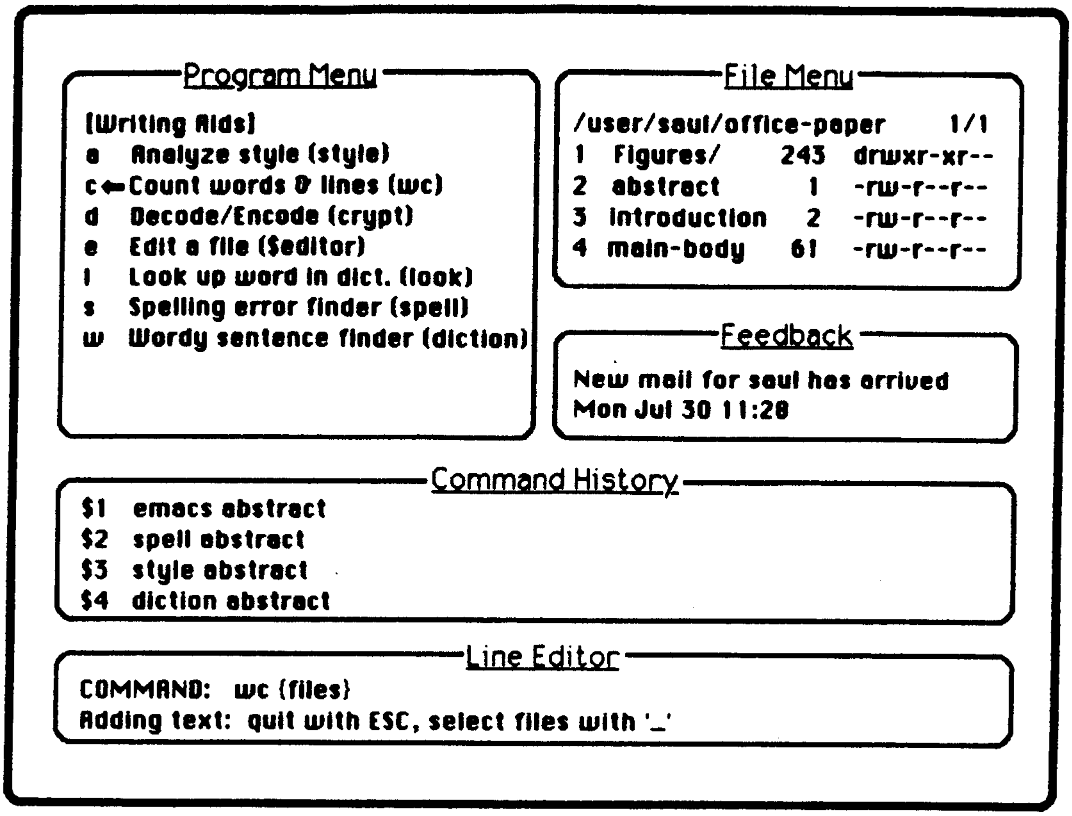


Figure 8.2: A stylized MENUNIX screen

with the file. If it is a directory file, the current working directory will be changed. If it is an executable file, it will be run (after arguments are requested). If it is a text file, the user's preferred editor will be called on it. Thus users are able to edit files and change directories with just the file menu commands.

Programs are structured into "workbenches", and the program menu displays names (brief descriptions) of the programs in the current workbench. For example, one programming workbench contains sub-workbenches for general programming and specific programming languages. Other workbenches gather writing tools, deal with mail, and so on. When a program menu entry is selected, arguments are requested and the program is executed. To implement the hierarchy, an entry in a workbench may point to another workbench (in the same way that an entry in a directory may point to another directory in the file hierarchy). Selecting one of these entries will replace the current program menu accordingly. Of course, one consequence of having a program menu is that the vast selection of UNIX utilities must be structured somehow into reasonably small subsets fitting into each workbench; otherwise the menu would become unmanageable. In MENUNIX, this is the responsibility of the system administrator.

MENUNIX fulfills one of the workspace suggestions by using the workbench metaphor to gather groups of activities. Yet it fails as a workspace for two reasons (Table 8.2). First, it does not support most task switching activities. Only one workbench is visible at a time, and traversing the hierarchical links between them is tedious. Outputs of previous selections are not even available when the next activity is being composed. Second, the end user is not expected to personalize his workbench. Yet not all programs fall neatly into the workbench paradigm; some tools may not be in the location in which the user expects to find them.

Object Browsers. Whereas command-based systems have a multitude of independent and unstructured tools, object-oriented programming environments take the opposite approach. Although systems differ by varying degrees (Stefik and Bobrow, 1986), object-oriented languages generally group data into abstract data types called *objects*, where "each object (or class of objects) has a set of operations (*methods*) to manipulate the data stored in that object" (Hailpern, 1986). These objects are usually arranged in a hierarchy or lattice, and every object *inherits* and builds upon the characteristics of its parents. Objects cannot directly manipulate either the data or methods attached to other objects. Instead, they send *messages* to each other that communicate requests.

A few programming environments take advantage of the highly structured relationships between the objects they contain by providing a workspace — called a "browser" — for creating, viewing, and manipulating objects. Through browsers, users can: a) view and traverse the object hierarchy; b) view particular object descriptions, their methods, and related comments; c) edit the objects and the methods; and d) change the relations between objects in the hierarchy. Depending on the environment and language supported, browsers also have different capabilities. The SMALLTALK browser, for example, differentiates between the object's class and instance methods (Goldberg, 1984). LOOPS, on the other hand, supports multiple inheritance (Bobrow and Stefik, 1983), and the programmer can add, delete, rename, and split classes, and re-organize the lattice through the browser in a way that is not allowed in SMALLTALK (Stefik and Bobrow, 1986).

Figure 8.3 shows an example of the SMALLTALK browser in action. As shown, the browser is made up of five subviews. The top four are menus that display, from left to right, class categories, classes, method categories, and message selectors. The large bottom subview is used mainly for editing templates of methods and class descriptions, although information about the object world is also displayed there (Goldberg, 1984).

What makes browsers particularly effective is the rigid classification of objects and actions within the environment. Unlike traditional systems (such as UNIX), each object understands only a limited set of actions. Similarly, action selectors (messages) are only understood by a restricted set of objects. A browser allows the programmer to inspect and use existing sets easily. When programming, objects and methods are easily added, deleted, and modified. Owing to the interdependencies between objects, it is vital for the programmer to view their relationships, for he must know how to extend existing objects, and which ones will be affected by any major changes.

Although object browsers are elegant workspaces for programmers, it is not clear whether this type of organization is reasonable for non-programmers. The browser's organizational strengths come from revealing the underlying structure of the object-oriented language, a structure that may be beyond the grasp and interest of a non-programming end-user. A further detraction is that although objects are extremely good representations of tightly related structures, they may be ill-suited for capturing the loosely related activities contained in task sets (Table 8.2).

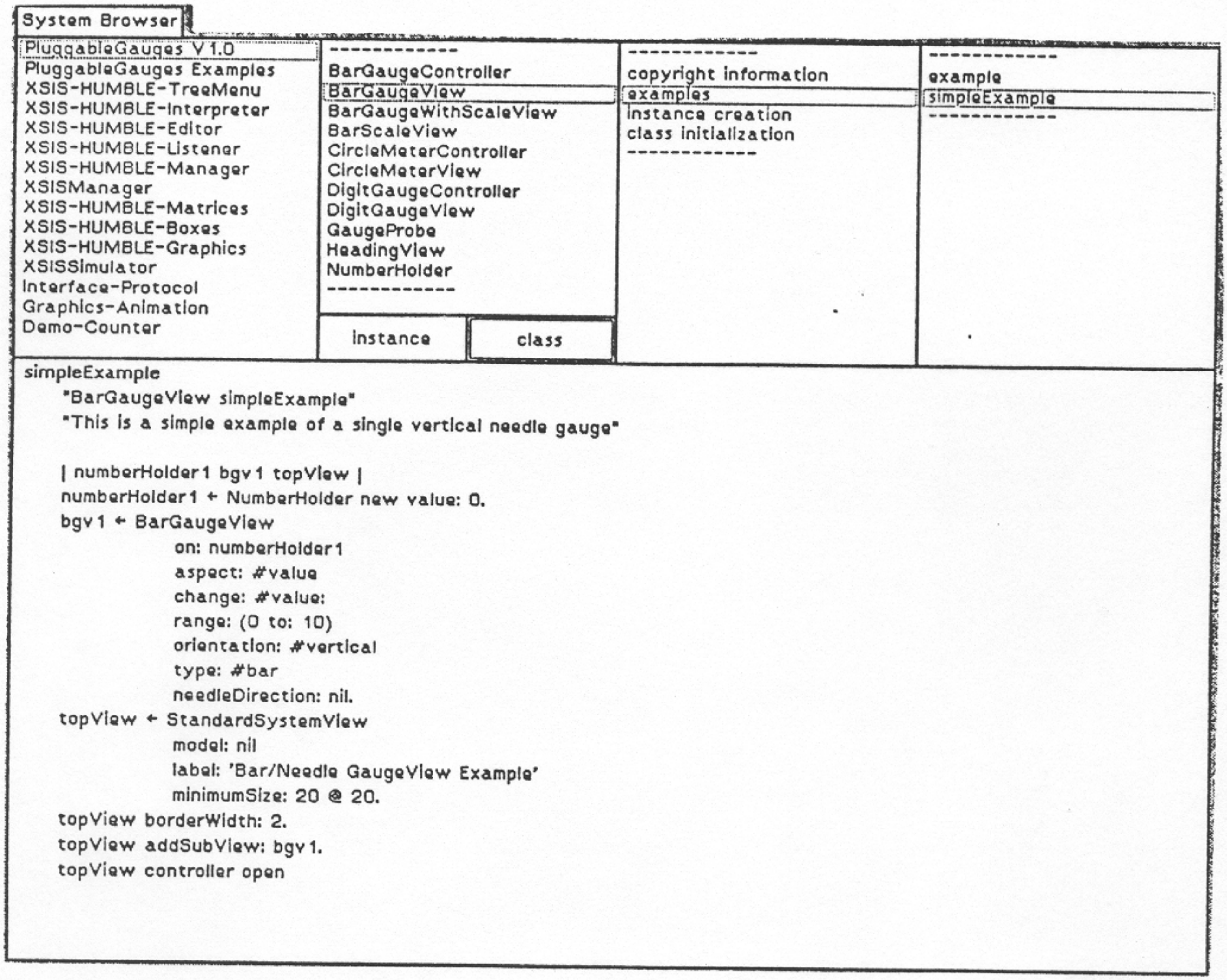


Figure 8.3: The SMALLTALK browser window

Multiple virtual workspaces. Window-based systems allow users to manage a set of windows on a screen, where each screen is considered a single virtual workspace. A multiple virtual workspace is produced when the system remembers different screenfuls of window sets and allows transitions between them.

Perhaps the most exciting implementation to date that represents this concept is *Rooms*, which divides groups of window-based applications into collections with transitions among them (Henderson and Card, 1986; Card and Henderson, 1987). Each screenful in *Rooms* is a virtual workspace containing windows running specific applications. Many virtual workspaces exist, and a user can switch tasks by supplanting the current workspace with the desired one. Although designed mainly to reduce "thrashing" effects occurring when one tries to keep desired windows visible on a small screen, it effectively allows a user to organize his collections of applications and move rapidly between them.

Rooms brings together tasks and high-level tools.

> When there is some task to be done, such as reading mail, writing a paper, or creating a program, the user gathers a number of tools for doing it ... The design of the *Rooms* system is based on the notion that, by giving the user an interface mechanism for letting the system know he or she is switching tasks, it can anticipate the set of tools/windows the user will reference and thus preload them together in a tiny fraction of the time the user would have required ... the set of windows preloaded on the screen will cue the user and help reestablish the mental context for the task.
>
> — Henderson and Card, 1986

A single room looks like a standard screen containing a few special icons called "doors," which link the current room directly with others. Opening a door follows the metaphor of changing rooms. Every room also has a back door leading to the

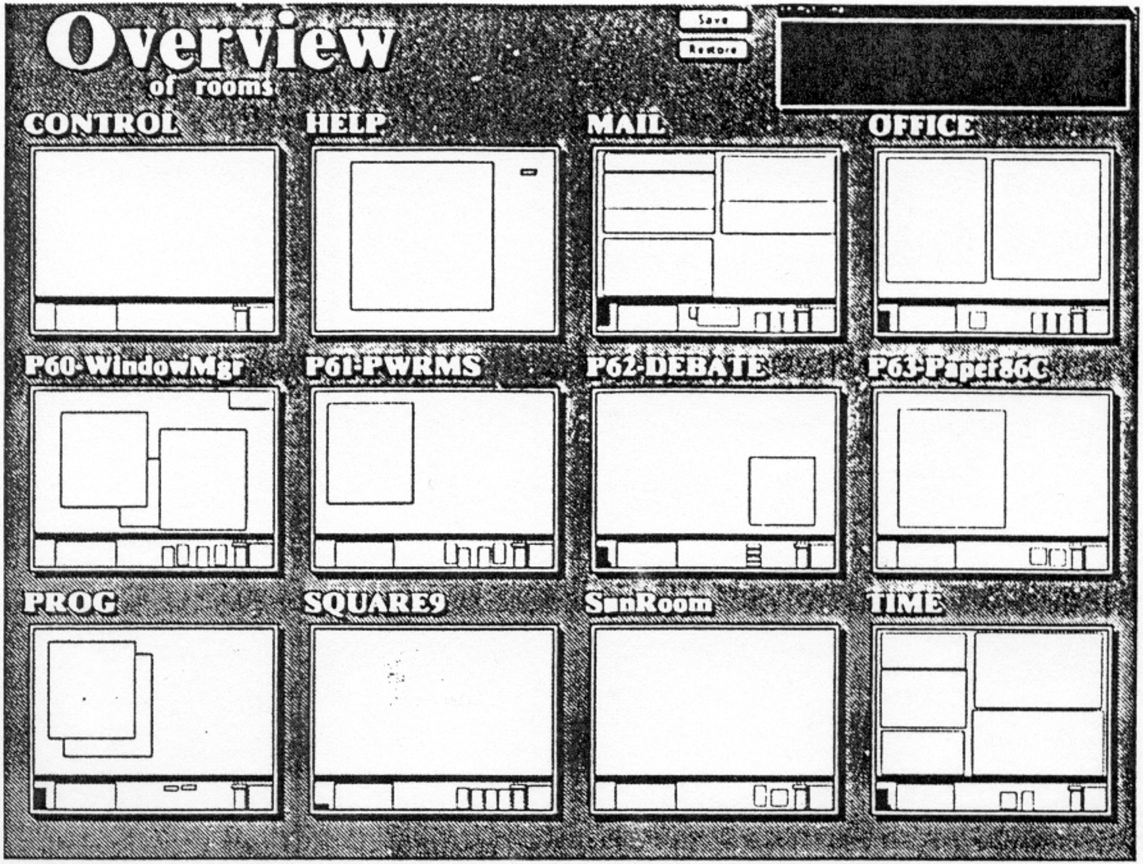


Figure 8.4: The *Rooms* overview screen, from Figure 10 in Henderson and Card, 1986

and allows users to choose between them through a desktop overview. And another UNIX-based system called *room* is a simpler version of the *Rooms* metaphor above (Chan, 1984). Here, icons are collected into workspaces, and each icon either invokes a UNIX process (including parameters) or leads to another room. A special icon called a "room maker" lets a user specify new icons. The workbench creation system (*wcs*) is yet another virtual workspace offering that preceded *Rooms* (Greenberg and Witten, 1985b). This experimental interface used windows to provide multiple independent views into workbenches that collected together a user's activities. What was novel about *wcs* was that activities executed through pop-up menus attached to the workbenches were user-defined and maintained through a specialized direct-manipulation editor. All important aspects of the *wcs* are contained in the implemented design detailed in the next chapter. A system somewhat similar to *wcs* was developed later by Dzida *et al* (1987).

Rooms only allows users to bundle together windows running high-level applications (*ie* appliances→ §1.2.2) with high-level tasks. But as seen in UNIX, much activity is generated at a low level, in that old lines are reused and new ones are formed continuously. Since there is no way to save a set of equivalent low-level activities in *Rooms*, its value in a general-purpose environment is probably not as high as it could be. Informally speaking, *Rooms* organizes workbenches within workspaces, but not the tools contained by each workbench (Table 8.2). Chan's *room* system, on the other hand, does provide this capability, albeit at a primitive and perhaps tedious level (Chan, 1984) (Table 8.2).

Concluding Remarks

This chapter provided evidence that computer users organize their activities in a variety of loose ways, most notably as collections of interleaved task sets. The findings suggest the notion of a workspace — a software tool that allows one to collect and arrange related materials into an explicit structure. Workspaces allow personalized grouping of activities and rapid task-switching between these groups. Furthermore, activities and their related attributes can be represented by symbols, and structures can be built by collecting together one's previous — instead of anticipated — activities. Several implemented designs were summarized and their properties contrasted in Table 8.2.

This chapter is intended to set the scene for future studies, experiments, creative design, and evaluations. The work presented here is a pioneering effort, and is currently incomplete. Empirical efforts for eliciting and understanding user organizations have just begun. The notions behind a workspace are also weak, for none have been evaluated and tested to any great extent. For example, no one has directly investigated user-composed symbols[3]. Similarly, it is not clear how well users can articulate their task sets. What seems reasonable in theory may fail in practice.

[3]The closest study is one by Good *et al* (1984), who suggest that user-derived commands improve a novice's ability to interact with a command system.

Chapter 9

A Workspace System: Description and Issues

> Basically, this workbench is composed of a pair of storage cabinets, on which rests a rugged work top. The exact design of the storage cabinets depends on the kind of work you do, the kind of tools you use, the amount of space you have.
>
> — Homeowner's How-to Treasury, Popular Science, Harper and Row, 1976, p214

This chapter describes a design and implementation of a user support tool that embodies the reuse properties suggested in Chapters 4 through 7, and the workspace organization of Chapter 8[1]. Called *Workbench*, the system is a graphical window-based front end to UNIX *csh*. The facilities and user interface are described in the first section, along with the rationale behind its design. *Workbench* is not an end in itself. Although recently made available to selected members of the local Department of Computer Science and now used by several people, it serves here as

[1]Some of the ideas in this chapter were presented at the Canadian Information Processing Society (CIPS) National Conference in Montreal (Greenberg and Witten, 1985b).

an exploration of a workspace design. It is not formally evaluated; experimental appraisal is neither credible nor necessary at this early stage. Rather, the intent is to discover how feasible it is to build a workspace, to note initial pragmatic considerations arising from its use, and to suggest research areas motivated by problems encountered or envisaged. These issues are covered in the second section.

9.1 The *Workbench* system

Workbench is a window-based facility that allows people to reuse and structure their on-line UNIX *csh* activities. It runs within the Sunview 4.0 window environment, and uses only the standard and familiar user interface constructs provided, such as panels, buttons, pop-up menus and so on (Sun Microsystems, 1988). For consistency with other Sunview applications, no attempt was made to change the "look and feel" of these constructs. Although it caused a few problems, following this standard nicely separated secondary interface design issues of window-based applications from primary aspects of a workspace.

The first subsection below gives a brief account of the several standard Sunview interface constructs used. The subsequent ones provide an overview of *Workbench*, describe in detail its activity reuse facility, its organizational capabilities, and finally the underlying architecture.

9.1.1 A brief overview of Sunview

Sunview is a user-interface toolkit that supports creation of interactive text and graphics-based applications running within a window environment available on Sun workstations. Although the building blocks supplied are moderately flexible, their usage in the *Workbench* design was limited to follow the standard user interface conventions pursued by most other Sunview applications. The look and feel of a few of the Sunview facilities selected are described here — frames, subwindows, ttys, panels and their items, alerts, and menus. Programming details are omitted; they are amply covered elsewhere (Sun Microsystems, 1988). A passing familiarity with window systems is assumed.

A *frame* acts as a window does in most window-based systems. It can be resized, moved around the screen, shrunk to an icon representation, selected for input, and so on. A frame is a Sunview object that brings together one or more other objects — frames or sub-windows — into a common framework so that they can be operated on as a unit. It can own non-overlapping *subwindows* that are constrained to fit within the frame's borders, and other *sub-frames* that are usually used to implement pop-up windows. Within a Sunview screen, a user will typically have several opened and closed windows on display (closed forms are represented by icons). Only one window at a time can receive textual input, chosen by moving the cursor into it[2].

Four types of subwindows are available: canvas, text, panel and tty. Programs can draw on a *canvas*, and text is presented and edited within *text* subwindows. The *tty* is a terminal emulator, and only one is allowed per frame. *Panels* are subwindows that contain a set of controls, called *panel items*. Although subwindows do not overlap, they can be moved about in the frame under program or user control.

Menus are pop-up lists that display several choices for exclusive selection. Although menus can present non-executable information, a selection usually performs some system action. By convention, menus appear only when a user depresses the right mouse key, and disappear on its release. Pointing to a menu item highlights it, while releasing the mouse key on the highlighted choice selects it. Special *pullright* menu items, distinguished by an arrow on their right, can display further menus. These sub-menus appear when the user moves the cursor rightwards on the item.

[2] Alternatively, Sunview windows can be configured to accept the input focus by clicking a mouse key within it.

Although there are many types of panel items, only the few used in the design are described here — buttons, cycle choices and text items. *Buttons* are items that usually display a framed text string or a graphical image, and are selected by depressing the left mouse key and pointing to it, which inverts its color. An action is triggered when the mouse key is released. Moving the cursor off a button de-selects it. Menus may be attached to buttons, and they appear when the right mouse key is depressed. Next, a *cycle choice* item allows the user to cycle through choices in a list. A descriptive text string is displayed on the left, the current choice on the right, and two semi-circular arrows in between. A left mouse key click will cycle through the available choices one at a time, while depressing the right mouse key raises a menu of possible choices. Finally, *text items* display a label followed by an editable string field. Pointing to the field highlights the text and moves a text cursor into it. Editing capabilities are primitive: the cursor can appear just at the end of the string, and only backspace, word erase, and line erase are supported. When more characters are entered than will fit in the field, the displayed string is scrolled to the left. The presence of hidden characters is indicated by a left-pointing arrow.

Alerts are pop-up sub-frames that display a message and a set of buttons in a panel. As indicated by their name, they alert the user of some event. Unlike other sub-frames, the alert takes control of the entire screen until the user responds to it. These frames are distinguished visually from other windows by a large arrow that sweeps into them.

The Sunview window system, although popular, is by no means perfect. It is painfully slow on low-end workstations (*eg* the Sun 3/50), especially for manipulating and switching between windows and for displaying menus. Certain interface features are annoying. For example, new windows usually appear at random screen locations, and several standard Sunview objects are difficult to use (*eg* scroll bars are functionally overloaded). From the programmer's perspective, it is easy to create applications that follow standard Sunview utilities. However, altering the interface look or behaviour is considered difficult. Greenberg *et al* (1986) discuss broader issues in the design of window management systems.

9.1.2 An overview of *Workbench*

The rest of this section describes *Workbench*. Since print on paper is a poor medium for explaining highly interactive systems, snapshots of the workstation screen are used to help convey the nature of the interface. The text is also annotated with notes indicating why design decisions were made and some of the problems encountered.

Workbench loosely follows the metaphor of a handyman's real workbench. It has three visual components on permanent display, presented as the three horizontally-tiled sub-windows illustrated and labeled in Figure 9.1. These are the *work surface*, the *tool area* and the *tool cabinet*. When the *Workbench* frame is closed, it shrinks to a pictogram of a physical workbench, shown by the icon at the top left of Figure 9.1.

The *work surface* is the tty subwindow on the bottom running *csh*, and is the main working area on workbench. When it is selected as the focus of attention, all lines entered through typing are processed by *csh* in the usual way.

The middle subwindow is the *tool area*. It includes a *reuse facility* for storing, selecting and editing lines entered to *csh*, and a *tool panel* for keeping several activities on hand independent of history. The tool area is analogous to the surfaces surrounding a real workbench where recently-used and favoured tools are kept on hand. It is a Sunview panel that includes three columns of text items and a button (Figure 9.1). The first two columns are the reuse facility, and up to eleven lines from a history list of *csh* input are displayed there. The third column makes up the tool panel where up to six favoured activities can be stored. Selecting any text item with the middle mouse button inserts the text into the work surface, which results in its execution by *csh*. The left mouse button enables editing, copying and pasting

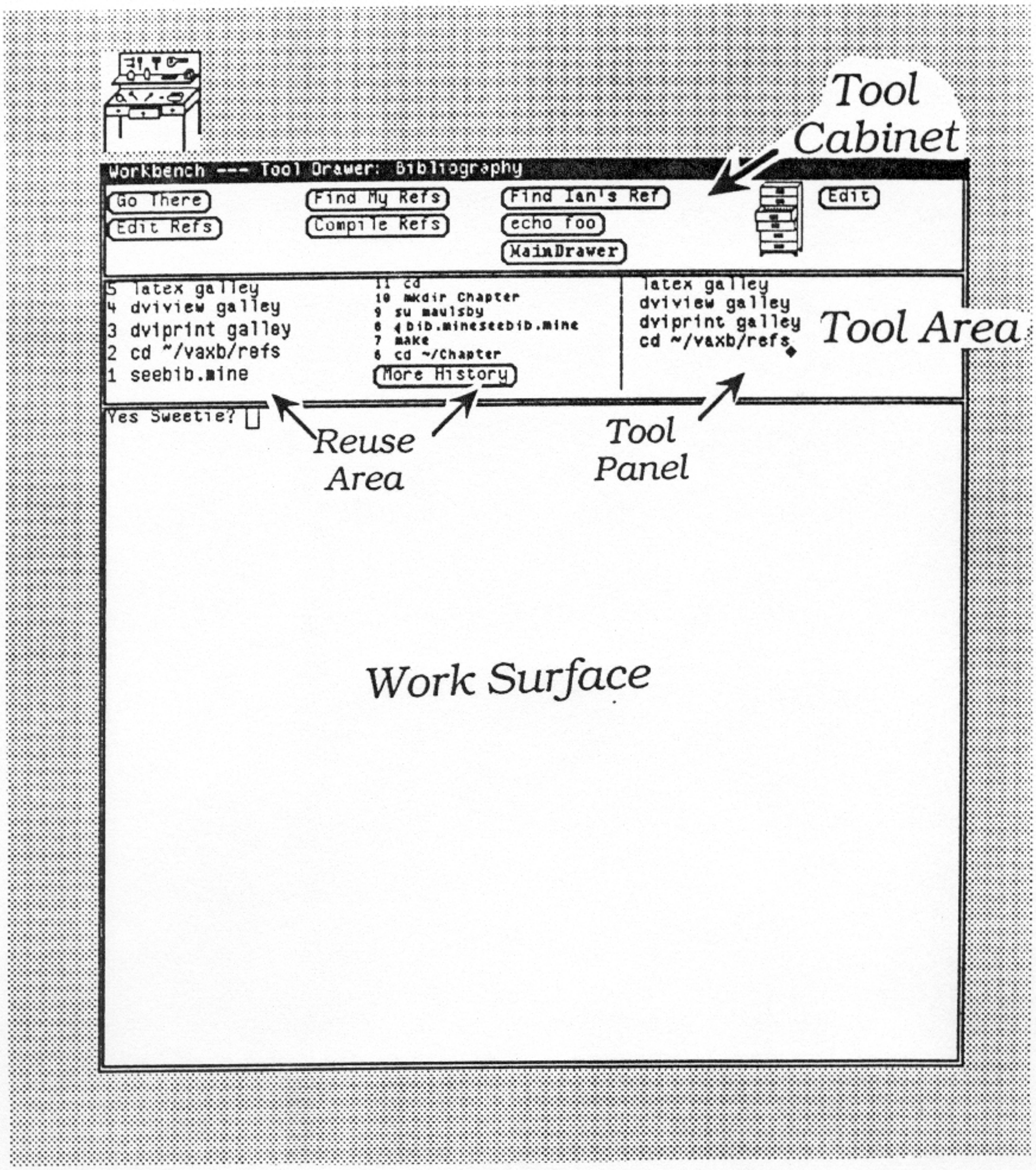


Figure 9.1: The normal appearance of the *Workbench* window

— a left key-press highlights the text and internally stores it in a copy buffer, while a shift-left pastes the stored string into a new text item[3]. Through copy and paste, the user can move text from the dynamic history list to the static tool panel.

> *Note 1.* The use of text items by *Workbench* is non-standard, for Sunview does not consider them to be buttons. An alternative design could place a real button next to every text item and use that for selection instead. However, this adds complexity to the interface and also consumes more screen space.

> *Note 2.* While button actions are invoked by clicking the left key on the mouse, text items use the middle key for an equivalent action. This is inconsistent. Switching the text item's left and middle key responses is not a solution, for it would make *Workbench*'s treatment of text items inconsistent with other applications. Neither design is satisfactory.

The *tool cabinet* is situated in the top subwindow of Figure 9.1. Through it, the user may open and display one of the many *tool drawers* available. Drawers contain both *tools* and *drawer handles.* Both are represented as labeled buttons distinguished by different text fonts. Selecting a tool inserts a UNIX command line into the worksurface subwindow, while choosing a drawer handle opens a new drawer in the cabinet, replacing the current one. The cabinet icon on the right allows the user to cycle through the drawers just visited (left mouse button), and to review and select from a menu of the drawers opened in the current login session or of all drawers available on the system (right mouse button). Finally, selecting the *edit* button on the panel's right pops up a frame containing an editable representation of the current drawer.

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[3]This violates the Sunview copy/paste standard, which uses a facility called the selection service. Only time constraints prevented its proper implementation here.

Note 3. ***Workbench*** by itself is not meant to handle all task-switching properties addressed by a workspace. Rather, it should be available as a window within a *Rooms*-style environment→ §8.3. While *Rooms* provides ways of collecting and switching between windows and their associated applications, ***Workbench*** provides ways of maintaining and organizing application- and task-specific details within a window. Due to time constraints, a *Rooms*-style environment was not implemented around *Workbench.*

9.1.3 Designing the tool area

Eleven previous submissions are always available for selection in the reuse portion of the tool area (Figure 9.1). The submissions presented are continuously updated to correspond to a history list maintained internally by *Workbench.* The numbering corresponds to the order of items maintained on the history list (*eg* item 1 has just been entered). These items are presented in a fish-eye view, where the font size of the text decreases with its probability of selection. If the user wishes to view more than eleven items, he may choose the *More History* button, which raises a pop-up frame containing thirty-nine further predictions (Figure 9.2, right side).

Note 4. Given the findings of previous chapters, eleven items seems a reasonable number. They do not consume much screen space and there is little gained from adding more. Eleven choices may be too many.

Note 5. The fisheye view is a tradeoff between legibility and screen area. Although the more probable items are easily read, the small size of items in the second column may preclude their use. Unfortunately, control of font size is not as rich as it could be — only three are available in Sunview.

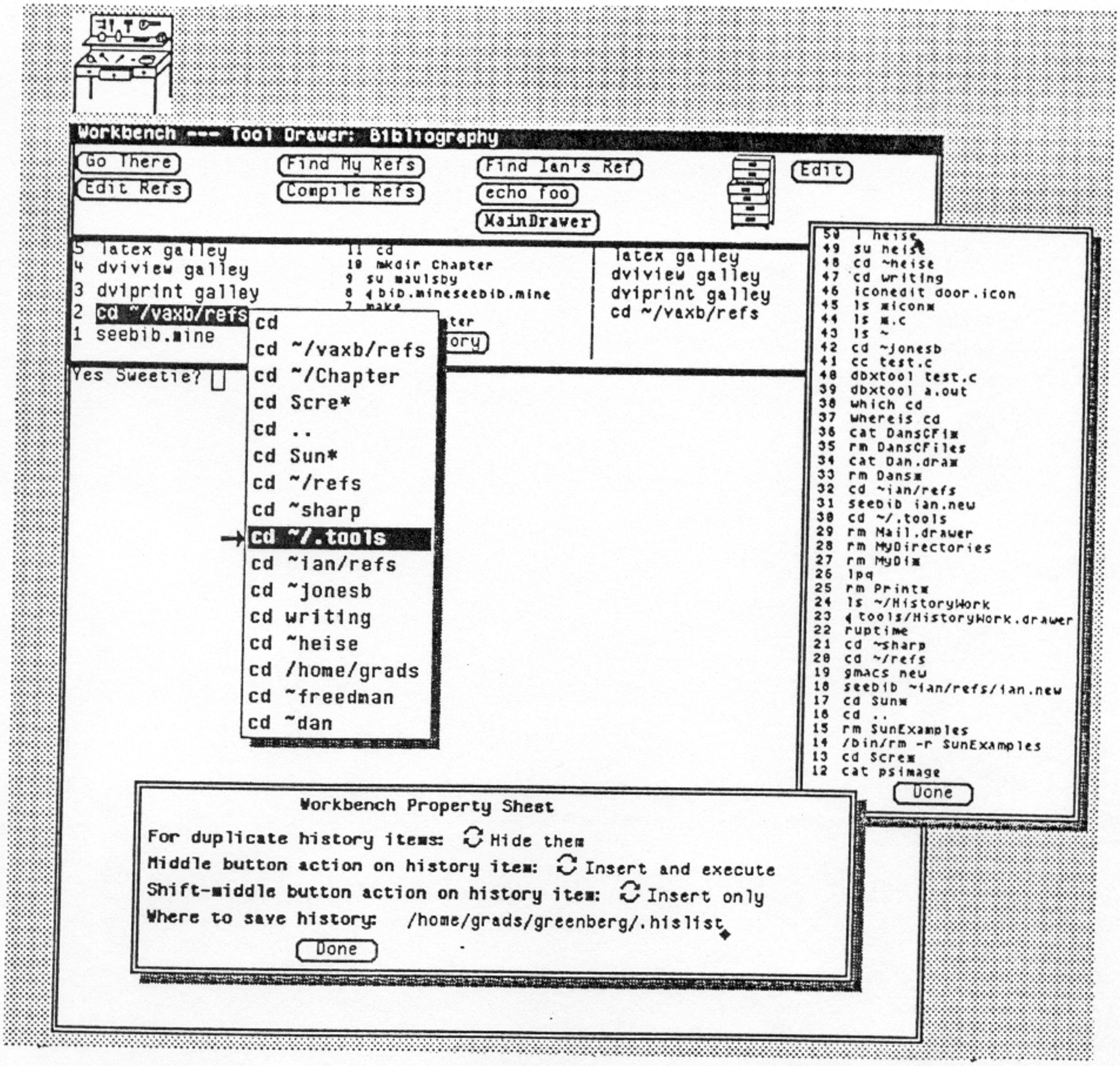

Figure 9.2: Ancillary controls of the tool area

Note 6. The reuse list is numbered and read from the bottom up. Although top-down presentation may seem intuitively more natural, the current ordering and addition of new items follows the scrolling direction of the text in the work surface.

The history list of *csh* input lines can be presented in several ways. By default, previous submissions are presented as a recency-ordered list with duplicates removed. Alternatively, the user may request duplicate items to be shown by toggling the cycle choice item on the *workbench property sheet* sub-frame — raised through a pop-up menu attached to the *More History* button — illustrated near the bottom of Figure 9.2. The user can also display command-sensitive sublists by raising a context-sensitive menu attached to all text items. Figure 9.2, for example, shows the sublist for all the different ways the user has submitted the frequently-used *cd* command. The menu also displays the full view of the current selection, which is important for long strings that are not completely visible within the text item. The expansion alone is also available through a non-standard shifted mouse-right key press.

Note 7. Recency-ordered history lists and command sensitive sublists follow the design recommendations set out in Chapter 7. Although an option for showing duplicate items is provided, it seems unnecessary in practice.

Users may change the behaviour of the middle button key on a text item through the above-mentioned pop-up property sheet. Although the key press will always insert the text into the work surface, the user can specify whether the line should be executed (which adds a terminating line feed).

Note 8. Insertion without execution theoretically gives the user a way of avoiding an erroneous selection by allowing him time to reconsider his choice. But error handling is not so easily solved, an issue discussed further in Section 9.2.

Any text item in the reuse area is editable, and the edited version will be executed upon selection. However, the original form will be maintained properly on the history list. In Figure 9.2, for example, if item 5 (*latex galley*) is changed to *latex galley-test* and then selected, the new version will then appear as item 1, while the original form moves on to item 6. If the edited item is not selected, it will revert to the original text after the next update.

> *Note 9.* As previously mentioned, Suntool text items have poor editing capabilities. This is frustrating, for even simple text modifications are tedious and usually not worth the bother. The only real value of editing is that text is easily appended to an item (which supports the partial matching by prefix method → §6.1.2). Sunview will support proper editing in the near future.

Workbench remembers its current state between sessions in several files. By default, history is saved in one location only. However, the user can also save (and optionally restore) his history in different files through the workbench property sheet (Figure 9.2). For example, using a relative file name will make the history list directory-sensitive on startup. Through a pop-up menu attached to the *More History* button (not shown), one can save, clear, or load the history from or to a file at any time during the session.

> *Note 10.* Chapter 7 indicates that directory-sensitive history lists provides some predictive benefit. Although saving history in different files lets users open workbenches primed to certain activities, this probably will not be used. Directory-sensitivity should be properly integrated in the next version of *Workbench* as an option.

Finally, users can type or copy executable lines from the reuse area into any one of the editable six text items in the tool panel. The text remains in place until it is next edited by the user, *ie* it acts as a tool cache. Copying is fast; several items can be transferred in a few seconds. Furthermore, items in the tool panel respond to mouse selections in exactly the same way as do text items in the reuse area.

Note 11. An alternate design of the tool panel considered placing history selections into empty slots, taking advantage of the fact that users continually recall the same activity when using history→ §7.1.1. This feature was not included due to the danger of overloading the tool panel's functionality.

9.1.4 Designing the tool cabinet

The tool cabinet displays a drawer at a time. The drawer's name appears in the title bar of the *Workbench* frame, and its contents are located in the top subwindow. Entries in a tool cabinet drawer comprise four types, where three are presented as text buttons and one as a pictogram. The first is a *tool* that invokes a Unix command, which is inserted and executed in the work surface upon button selection. The second is a *drawer handle*, whose selection will close the current drawer and open a new one. The other two are special-purpose edit and cabinet buttons.

A tool has three internal components; an executable string, a short label, and some help text that describes the tool's function. Only the executable string is mandatory. Tool buttons display the label (if there is one), or as much of the executable string as will fit. At any time, the user can raise a help menu that displays the help text (if any is available) and the executable command. Figure 9.3 illustrates the help menu for the tool button labeled *Edit Refs*. The help string *Edit my refer file* appears as the first menu item, followed by the executable string *gmacs*

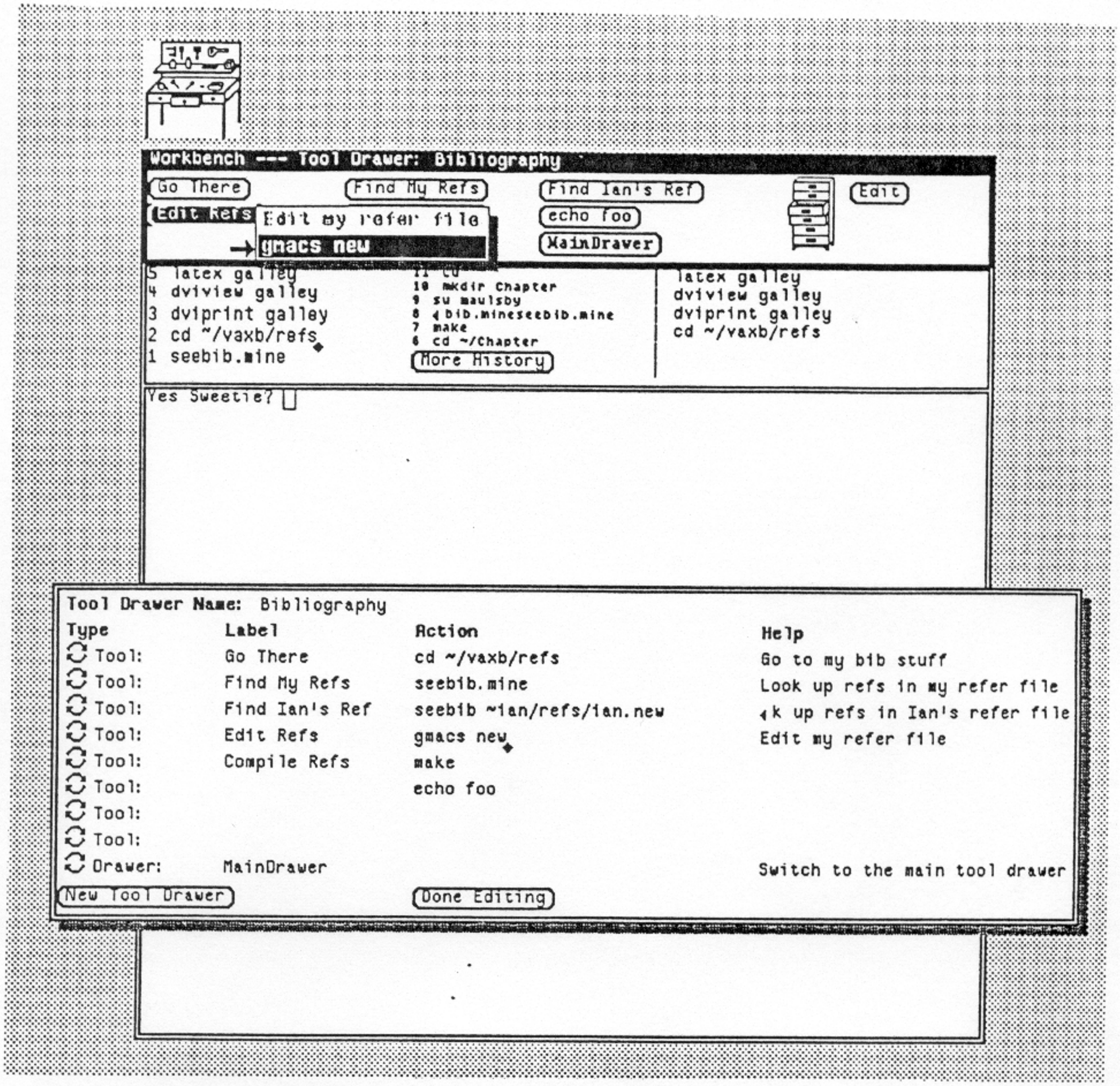

Figure 9.3: Ancillary controls of the cabinet

new. The user invokes ***gmacs new*** by either clicking on the button or selecting it from the help menu.

A drawer handle has only two components; a short label which is also the name of the drawer to be opened, and a help string. The label is displayed in a serifed font to distinguish it visually from the sans-serifed tool button. The help menu works the same way as the one described above, except that no action is displayed. The button labeled *MainDrawer* in Figures 9.2 and 9.3 is one example of a drawer handle. If it were selected, the entries of the current *Bibliography* drawer would be replaced by the ones from MainDrawer. The title bar is also updated to reflect the drawer's name.

The cabinet pictogram is a button that offers another navigation scheme for drawers. Raising its menu shows a trail of all drawers visited. As with the reuse area, open drawers are maintained as a recency-ordered history list without duplicates. The user can choose a menu item to return to any previous drawer. Alternatively, clicking on the cabinet button will cycle back through the history list one drawer at a time. The user may also view and select any drawer available on the system through a menu raised via the middle mouse key.

Central to *Workbench* is the method of creating and altering the drawers and the items they contain. Without the ability to personalize it, the cabinet would have limited novelty and would contain no fundamentally new ideas, being simply a way of allowing users to navigate through a predetermined network of utilities. But the inclusion of an end-user creation/maintenance system provides an interesting medium in which to explore explicit user personalization in a rather sophisticated interface. It is essential to success that modification be quick and easy, for if not, novice users will be denied access to a tool which should make work much easier for them, and expert users will not alter the support structure to reflect changing requirements.

The user defines drawers in the first place by filling out and editing a simple form, raised as a pop-up window by selecting the *edit* button on the tool cabinet (Figure 9.3). The top line of the form shows the name of the drawer, while each subsequent line represents the attributes of a single drawer button. The choice item sets the button type as either a tool or a drawer handle. The three other fields in the line are editable panel text items that specify the label, action (for tools only), and help associated with each button. Figure 9.3 shows a snapshot of *Workbench* with the current *Bibliography* drawer opened for editing. The relation between the drawer's items as shown in the cabinet and in the form should be self-evident.

> *Note 12.* Users are invited to document their tools when created by attaching a meaningful symbol to an action, and by annotating it with help. This ameliorates one of the most severe drawbacks to explicit personalization schemes — that a user becomes confused and disoriented when faced with another's model (and perhaps even with his own). Although there is no check that the user-supplied label and help information is accurate, the fact that it can be provided should encourage sensible use. However, attaching help to buttons is non-standard in Sunview.

A user edits or expands an existing drawer by traversing the network in the normal way and then selecting the *edit* button, which always displays the current drawer. New ones are created by selecting the button labeled *New Tool Drawer* at the bottom left of the form and filling in the vacant fields as desired. Drawers are linked to each other by changing the item type to a drawer handle and filling in the appropriate name in the label slot. The user quits the editing session through the *Done Editing* button, and an alert box gives him the option of saving or discarding any changes made.

> *Note 13.* The user has no support for globally examining, modifying or removing links between drawers. This lack is quite serious. Sec-

tion 9.2 will discuss this deficiency and raise other general concerns of user-created networks.

Note 14. If a user wishes to create an explicit link to an existing drawer, he must recall and type it in, a highly error-prone activity. A better method would attach a menu to the label field of the drawer handle that lists all the drawers available and inserts the name selected.

A novel and necessary feature of the drawer editor is that activities can be copied from the history list or tool panel to the current drawer item. The method is the same used to transfer text within the tool area. In fact, lines can be copied from one text item to any other throughout *Workbench.*

Note 15. The current system follows the simple strategy of copying straight text from one text item to another, a clearly limited approach. One should be able to select and group multiple fields and multiple lines for copying as a single entity. This would reduce tedium for the user who, for example, wishes to package all his tool panel items into a drawer.

The drawer editor sketched above is a user interface prototyping scheme for creating simple interfaces with control panels. With it, end users can easily and interactively build a window interface for a command-based interactive program. For example, a UNIX software tool with a plethora of switches to generate different variants of its behaviour can in a matter of minutes be given a smooth, window-based, interface which is controlled by buttons, each having pertinent context-dependent help. Similarly, activities surrounding a task can be pulled off the tool area and packaged as a drawer.

9.1.5 Underlying architecture of *Workbench*

Workbench is an independent UNIX process that communicates with application programs. Upon invocation, it creates a unique UNIX socket (Sun Microsystems, 1986b), and then spawns a single new *csh* process. While *Workbench* is listening for any messages sent to it, *csh* searches for and establishes one-way communication through the socket. *Workbench* then becomes a receiver that collects historical activities directly from *csh*.

As a sender, *Workbench* does not communicate directly with *csh*, but merely inserts text into the workspace. The current application receives the text as if the user typed it in himself.

> *Note 16.* Multiple applications running concurrently can be supported by this architecture, as *Workbench* can receive messages from *any* process that sends to it (although only *csh* is used in this version). By maintaining and switching between different history lists, the presentation of activities on the tool area could then be application sensitive. This theme is expanded upon later.

History is maintained in a data structure that allows *Workbench* to present the list rapidly under three conditioning methods: sequential order showing duplicates, sequential order with duplicates shown in latest position only, and as a command hierarchy with command-sensitive sublists. Although not particularly elegant, the data structure serves its purpose quite well. Figure 9.4 illustrates how some of the lines shown in Figure 9.1 are maintained. As shown, the true history order is maintained as a linked list, where each node (called a line node) points to its corresponding command line, maintained separately in a binary tree (far left of the figure). Many line nodes may point to the same line, as only one copy is retained. Displaying the n most recently entered lines is simply a matter of getting the lines attached to the first n nodes at the head of the list.

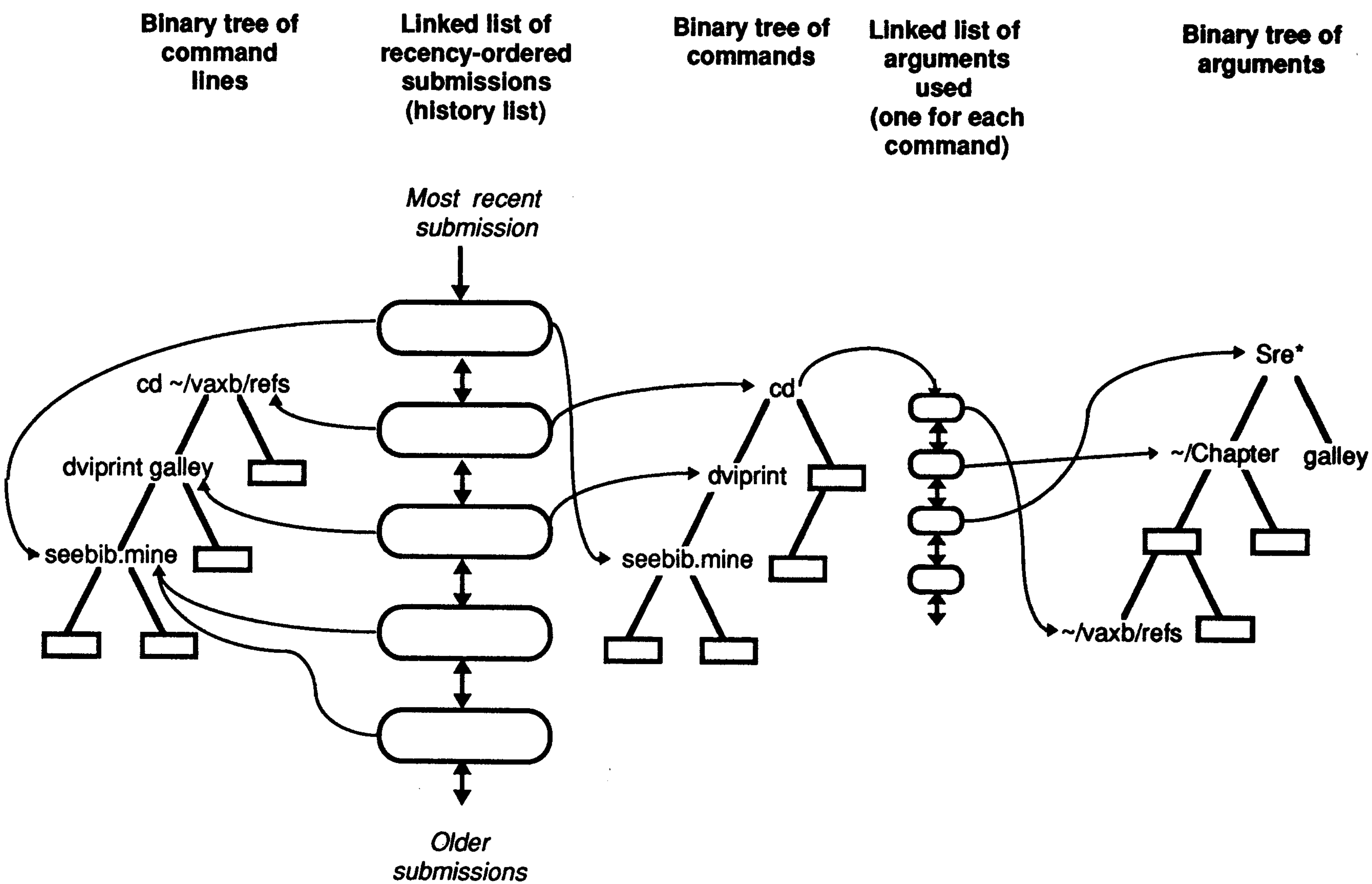

Figure 9.4: The data structure used to maintain the history list of activities

The method for retrieving n lines with no duplicates shown is slightly more complex, for it avoids pattern-matching as a method to determine if something has been seen before. It relies upon integer markers stored with every line in the binary tree and a single global counter, all initialized with values of zero when *Workbench* is first invoked. Detecting duplicates is straightforward when each is set appropriately. When the view of the history list is to be updated, the global counter is first incremented to make sure that its value differs from all markers. Each line node is then visited in order. If the marker and counter differ, the item is presented and the marker set equal to the counter. If they have the same value, then the item has already been presented. The process terminates when the required number of items are found or when the history list is exhausted. There is no need to update nodes which have not been visited.

Command-sensitive sublists are maintained separately by using two additional binary trees (Figure 9.4, right side). One stores unique copies of all the commands (*ie* first words in lines) seen so far, while the other contains all arguments (remainder of lines). Every node in the binary tree of commands maintains a recency-ordered linked list of pointers to the appropriate arguments in the other tree. This becomes the command-sensitive sublist. Since every line node also points to its corresponding command node, finding and retrieving the list of arguments is fast. Figure 9.4, for example, shows how the last three arguments used by the *cd* command are stored (also displayed in pop-up menu of Figure 9.2). Duplicates are processed in exactly the same way as the duplicate-removed history list mentioned previously. Again, no pattern-matching is required to update the list.

> *Note 17.* Presenting and updating the history list is quite rapid, even when the auxiliary pop-up history panel is displayed. The user does not have to wait for the system to catch up with him. Similarly, the command-sensitive menu appears almost instantly. But given the speed of most window-based workstations and the relatively small values of n

and of items maintained in history, the data structure used may seem overly complex and unnecessary. However, an early prototype built on a LISP machine performed poorly when items were maintained as a simple record of lines entered and retrieved through pattern matching.

Note 18. Another and perhaps more elegant data structure uses a single history list that maintains all pointers internally. For example, one chain of pointers would lead through the true sequential order; another would by-pass all duplicates, and so on. No counters need be maintained, as all information is provided by the links themselves. A hash table or its equivalent would be available for rapid indexing into the structure. While this structure is slightly more efficient than the one used, it is slightly harder to code in the "C" language used for this implementation.

9.2 Pragmatic concerns and research questions

In the design presented here, a workbench metaphor was adapted for a user support tool that keeps recently-used input lines available for selection and provides people with the capability of organizing their collections of lines. Yet several significant problems exist. First, serious engineering concerns arise from *Workbench* being just a front-end to an application. Second, several aspects of the design raises open research questions that need answering. Both themes are pursued in this section.

The lack of input redundancy. *Workbench* provides a way of executing an input line by a single press and release of a mouse key. As this eliminates input redundancy, it is quite difficult for the user to catch erroneous selections.

Consider a person who has written a document after removing an old one, where the actions displayed in the reuse area are *ls*, *rm document*, and *edit document*. After editing, the person decides to list the files (*ls*), but a sloppy selection mistakenly chooses the command that removes the newly created document. Destroying a day's work would certainly undermine one's confidence in *Workbench*, and could discourage its continued use. The same argument applies, of course, to menus and buttons.

The problem of no input redundancy is not peculiar to this design, but plagues any system that allows users to invoke an action in a single step. One sometimes sees attempts to add artificial redundancy. The tool area, for example, can be set to insert a line into the work surface without executing it. The user can then preview the line and accept it by hitting the return key. Similarly, every choice could be confirmed through an alert box. Yet neither are good approaches, for the act of acceptance often becomes a conditioned response. A better approach would include undo operations, of which many styles are available (Thimbleby, in press). Users could then aggressively explore and pursue their actions, for they know that they can backtrack to previous acceptable states at any time.

By itself, *Workbench* cannot hope to solve this problem, for it is just a front end to an application that may not have an undo capability.

Collecting and presenting input from different applications. Reuse facilities must somehow collect a user's input before it can be presented. One architecture considered uses a pseudo-tty input filter that collects *every* line before it is submitted to the application, and passes a copy to *Workbench*. This method is general purpose and requires no modification of the source code of an application. However, it has several disadvantages. First, input to some applications may not follow the pattern of recurrent systems (*eg* lines of free text). However, their entries would still be collected and presented for reuse. Second, items from all applications would be presented together, even though it is unlikely that the user could make use of lines submitted to one application in another (*eg csh* versus *lisp* input). Third, applications have no opportunity to massage input before passing it on. Errors cannot be treated differently, lines cannot be expanded, inappropriate submissions cannot be discarded, and so on. Effective reuse requires some applications to massage their input, as primitive activities may not be demarcated or well represented as a simple line. In *emacs*, for example, an activity could be an extended command line, which is denoted by an <escape-X> prefix. A hierarchical menu traversal may be represented by the name of the leaf node reached rather than (say) the function keys pressed.

For the reasons above, applications should be responsible for collecting, massaging, and passing on a user's input. Non-recurrent systems would not do this, and the reuse facility would be made application-sensitive by maintaining and switching between various history lists. Yet this is impossible in the current UNIX environment. Source code is rarely available, and the task of modifying even a few key applications is daunting[4]. Clearly, an integrated system incorporating history collection primitives would have to be designed from the bottom up. The Symbolics LISP environment is currently the only general purpose environment that embeds and supports a uniform reuse facility across all applications (Symbolics, 1985).

User-defined symbols. The cabinet encourages users to label and add help to all their tools and drawer handles. Although intuitively appealing, there is no empirical evidence that this is a good strategy. Do individuals remember the meaning behind their labels over time? Are help annotations useful? Can a person use a cabinet created by someone else? These are all open questions.

Forming and maintaining drawers in a cabinet. The cabinet has no inherent structure of its own. Users can only list all drawers, or chase their own explicit links

[4]Obtaining, understanding, altering and debugging the sparsely commented and undocumented source code of *csh* spanned a four month period.

between drawers. As a drawer can link to any other drawer, the navigation space is a network and is potentially complex. Yet it is not known whether personalized networks are usable in practice. Experimental evidence suggests, for example, that users of the UNIX hierarchical directory recall only half the names in their directory areas accurately after being out of touch with it for a lengthy time (Akin *et al*, 1987). Users were also seen to develop search strategies for misplaced files. However, since the cabinet relies on recognition rather than recall, it is not clear how well the UNIX results apply. Again, these are open questions.

The navigational problems of a cabinet are potentially as complex as the ones found in hypertext systems, and call for an equivalent support structure. At the very least, the network should be portrayed as a graphical map that allows users to visit and modify the contents of drawers and connecting links between them through direct manipulation. Methods should be incorporated to ensure consistency on modification. For example, changing a drawer's name should be reflected by all links.

Generalization. Tools in a drawer (and possibly lines presented by the reuse facility) could have greater value if their parameters could be generalized. Currently, *Workbench* only inserts a line into the work surface, and no facility is available to prompt for or to generalize its arguments[5].

Generalization can be implemented by having the user explicitly mark a variable. Perhaps a prompt would be specified, defaults indicated, a list of available choices provided and displayed as a menu, the input limited to a specific type, and so on. Information could be presented and retrieved through a pop-up property sheet attached to the tool. Similar methods have already been implemented to elaborate programming constructs after creating a macro by example (Halbert,

[5]This is not strictly true, for *csh* provides a way for a command line to get its input from subsequent input lines. For example, *echo "Show what file?"; cat $<* will print the prompt *Show what file?* and use the user's response as the argument to the *cat* command.

1984). Perhaps the system itself could infer the generalization.

But are users, especially non-programmers, capable of specifying and maintaining these potentially complex behaviours of tools in a dynamic general purpose environment? And is it worth their time and effort? No one knows.

Chapter 10

Conclusion

> If I send a man to buy a horse for me, I expect him to tell me that horse's points — not how many hairs he has in his tail.
>
> — Carl Sandburg's *Abraham Lincoln*

This final chapter will be brief. First, the argument of the thesis is reviewed. Next, the original contributions are identified. Finally, new directions for research are sketched. The individual components of the thesis are not evaluated or criticized because this has been done at the end of each chapter.

10.1 Argument of the thesis

We began with the observation that orders given to interactive computer systems resemble tools used by people. Like tools, orders are employed to pursue activities that shape one's environment and the objects it contains. People have two general strategies for keeping track of the diverse tools they wield in their physical workshops. Recently-used tools are kept available for reuse, and tools are organized into functional and task-oriented collections. Surprisingly, these strategies have not been transferred effectively to interactive systems.

This raises the possibility of an interactive support facility that allows people to use, reuse, and organize their on-line activities. The chief difficulty with this enterprise is the dearth of knowledge of how users behave when giving orders to general-purpose computer systems. As a consequence, existing user support facilities are based on *ad hoc* designs that do not adequately support a person's natural and intuitive way of working.

Admittedly, a few recent studies have analyzed people's behaviour when selecting orders. However, closer examination shows that they concentrate exclusively on commands (the verbs of the human-computer dialog), and ignore options (the modifiers) and other arguments (the nouns or objects) of the command line. Consequently, a new study was undertaken to characterize people's behaviour when selecting complete command lines.

Because of their potential for reuse, repetition of command lines deserved special attention. The problem is to identify likely candidates for reuse, and several ways of conditioning the distribution to enhance predictive power were evaluated. Several striking characteristics of how often people repeat their activities emerged from this study. They were abstracted from usage data gleaned from many users of different classes over a period of months. Reformulated as empirically-based general principles, they constitute design guidelines for a facility that predicts old submissions for reuse. A case study of actual usage of a widely-available history system provided a salutary reminder of the need for careful attention to design details.

So much for history and reuse. The next question was that of organizing activities by task and by function. An on-line facility called a "workspace" was described that allows people to gather together their tools for related activities. The problem is to identify the properties a workspace should have. Since our knowledge in this respect is limited, the properties were formulated as suggestions, and the list was augmented by creative ideas from existing designs that seem to capture some flavour of what a workspace should be.

Based on these suggestions, a system that loosely follows the metaphor of a handyman's workbench was designed and implemented. It includes a tool area made up of a reuse facility and a tool panel, where both recently-used and explicitly-cached submissions are kept available for immediate reuse. Through a tool cabinet, a person can organize his tools in drawers, and link drawers into a network by drawer handles. Any submission available on the history list can be copied and pasted into the tool panel or any drawer. Despite its principled design, the system illustrates that serious pragmatic problems are encountered when user support tools are bolted on to existing computer systems.

10.2 Original contributions

Absolute originality in the field of human-computer interaction is hard to come by. A very wide spectrum of ideas has been mooted in one form or another; anyways, human-computer dialogs are analogous to human-human and human-machine ones that have been developing for aeons and studied for centuries. For example, the idea of a reuse facility is clearly not new. Neither is the idea of a workbench. MENUNIX, *Rooms*, and the SMALLTALK Browser, surveyed in Chapter 8, can all be considered workbenches of one form or another. To find ideas absolutely original to this thesis, one must move to a finer grain of analysis.

There are two. One is the idea of conditioning history by command context to give better predictions. When combined with removing duplicates from the recency-ordered list, fully three-quarters or more of all recurring submissions can be chosen from a short history list (compared to two-thirds for a recency-only list). The quality of submissions presented is also higher, as measured by the length of text predicted. Since the order of submission entry is maintained, the user himself can predict the system's offerings and its location on the list, and not waste time searching for items that are not there. The second is the idea of using the history list as a primary source of tried and tested candidates for storage within the workbench organization. When combined with direct manipulation editing of workbenches (first mooted by Greenberg and Witten, 1985), a person can rapidly create, annotate, and modify his personal workspace so that it responds to his situated needs.

Aside from these two completely original contributions, there are a number of others which, while certainly important, have the character of more routine advances in human-computer interaction.

- In surveying studies of UNIX use:
  - faults and limitations of all data collection methods have been identified;
  - population statistics do not transfer well to individuals;
  - command lines are just as important as commands, if not more so.
- In a new study of UNIX usage:
  - growth of a user's command vocabulary is slow and irregular;
  - growth of a user's command line vocabulary is rapid, linear, and regular;
  - recurrence rates for different groups, although different, are quite high;
  - the probability distribution of recurrences over a history list is strongly skewed towards recency of entry;
  - methods for conditioning the distribution can be ranked by predictive quality;
  - a case study of UNIX *csh* history indicate how poorly it performs.
- In generalizing and validating the study:
  - a set of principled guidelines for reuse are offered;
  - testing a different system enforced the belief that these principles can be generalized.
- In analysis of history systems:
  - reuse facilities are categorized and surveyed within a new taxonomy;
  - recurrent systems are defined, and UNIX *csh* is described in that context.
- In the concept of workspaces:
  - people organize their online activities;
  - several design suggestions for a workspace are elaborated;
  - a principled design can be implemented on top of existing systems;
  - bolt-on user-support facilities are not the complete solution.

10.3 Looking to the future

The scope for future research into reuse facilities and workspaces is large. The first step, of course, is simply to get these ideas integrated into future computing systems. I see the next decade blending the expert-oriented general-purpose environments of the seventies and the special-purpose appliance interfaces of the eighties, perhaps through a metaphor similar to the workbench. First time and casual users will have a default workbench structure to begin with (created by the designer through discussion with users and analysis of their generic needs). It is a simple learning progression to go from modifying individual workbenches, to adding new ones, and finally modifying or creating new support infrastructures.

The exciting possibility of workbenches modifying themselves (possibly through consultation with the user) would go even further to ensure their effectiveness. I foresee an intelligent interface monitor which keeps track of user activities and offers potentially useful workbench configurations on request. When combined with a knowledge base, the monitor may infer tasks and the collection of tools required from just a few user actions, possibility through stereotyping with existing models (Rich, 1983). One consequence is rapid development of workbenches suitable for transient user actions. The next step, of course, is to use this infrastructure as a platform for coaching and advisory systems that detect bad task models and suggest alternatives.

There is still great scope for new research in user behaviour. Although this thesis has made a start, little is known about how people use, reuse and organize their online activities. Present reuse facilities leave considerable room for improvement, both in their user interface and in the predictive methods they incorporate. Our current knowledge of task formation and use is inadequate, and inferring a person's tasks from a trace is surprisingly difficult. It is not known how best one person's collection of tools can be shared with others. The idea of a workspace metaphor is immature. Existing workspace implementations are not widely available, and not one has been scientifically evaluated. The viability of richly-connected networks for organizing, linking and browsing through materials is still an open question, now being addressed by studies of hypertext systems. Finally, surprisingly little is known about personalizable environments. This gap must be filled if people are to create their own symbols, annotations and networks.

Tool use started when animals searched and used the debris of their natural environment to shape their physical world. It continues with people searching and using the tools of their computers to shape and manage their own intellectual worlds.

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Appendix A

Instructions to Subjects

This appendix notes the set of instructions given to subjects conscripted to the UNIX *csh* study undertaken in this dissertation. Instructions were not the same for all groups, for the subscription protocol depended upon the physical machine being used and the type of user. As these differences are trivial, only one typical set of instructions is recorded here. Several groups of subjects received essentially the same information in verbal form.

The packet sent to all users of *csh* in the Faculty of Environmental Design at the University of Calgary follows. The first page is a letter that asks the reader to take part of the study. The second gives instructions to those wishing to subscribe, and sooths a few obvious concerns that users may have.

Saul Greenberg
Human-Machine Systems Laboratory
Department of Computer Science
Room MA781 (220-7140)
email: saul

October 25, 1988

To: All users of the EVDS VAX computer

Dear Graduate Student, Researcher or Professor

As part of my PhD research in the area of human/computer interaction, I am collecting data on how individuals use commands in UNIX. My study groups include a variety of user types, ranging from computer novices and experts to non-computer scientists such as in faculties like yours. I would like you to participate in the EVDS study group. All you need to do is login to the EVDS VAX computer and type *trace <your login name>*. Detailed instructions are provided on the next page.

The users of EVDS VAX computer are important to this study. These users — of which you are one — tend to be around for a while, making long-term data collection possible. Also, recording the diverse nature of tasks done by the EVDS group is especially relevant to my research.

I would greatly appreciate your joining this study. As you will see from the attached instruction sheet, it is quite simple for you to become a participant. Enrolling should take no more than a minute of your time, and everything afterwards is maintained automatically. By the way, it doesn't matter if you use UNIX only occasionaly, or for only a few things – your participation is still needed!

I realize that you may be concerned about personal privacy. As the instruction sheet explains, I have gone to great lengths to ensure the confidentiality of any data collected.

If you have any questions, feel free to see, phone, or email me. Otherwise, just follow the instructions on the next page.

Thanks for your help,

Saul Greenberg

Instructions

Joining the study. If you have decided to participate in the study, log in to your VAX and type[1]:

trace <your login name>.

For example, if your login name is *smithj*, you would type:

trace smithj.

This command is only entered once ever. By the way, the name you use must be the same as the one you logged in with[2]. On the unlikely chance that you did something wrong, the system will tell you what to do. And that's all there is to it!

Quitting the study. When the study period is over, data collection will stop automatically. You won't even notice a change. If for some reason you decide to quit the study early, just type the following:

chsh <your login name> /bin/csh

Privacy. You may be concerned about privacy and confidentiality. I have gone to great lengths to make the data collected secure from prying eyes — no-one but me has access to the data files. Collected data that is referred to publicly (such as in a paper), will be anonymous. Also, the only data collected is that typed on the UNIX command line (such as *ls, ed, emacs* ...). I will never see the contents of your mail, text files, etc.

Performance. You will not notice any slow-down of the system. The time it takes to record the data is negligible. If the system ever seems slow, it has nothing to do with this study.

Side effects. There is only one cosmetic side-effect which you probably won't even notice. When you become a subject through that one-time use of *trace*, your login shell (called */bin/csh*) is switched to a different one (*saul/csh*). It functions as your normal login shell does, except that data collection takes place. The side effect is that if you ever invoke a system program which lists the complete path of the login shell, it gives the path to the new one.

Questions. If you have any questions or comments about anything related to this study, feel free to contact me (Saul Greenberg). You can do it in person (MA 781), by phone (220-7140), or by electronic mail (*mail saul*).

[1] The full pathname of this program is */usr/local/trace*.

[2] Thus you cannot subscribe anyone but yourself to the study

Appendix B

A Sample Trace

A portion of a trace belonging to a randomly selected expert programmer follows in the next few pages. The seven login sessions shown cover slightly over one month of the user's UNIX interactions, and include 128 command lines in total.

As mentioned in Chapter 2, all trace records have been made publicly available through a research report and an accompanying magnetic tape (Greenberg, 1988). This report may be obtained from either the Department of Computer Science, University of Calgary, or from the author .

Since the raw data collected is not easily read, it was syntactically transformed to the listing presented here. The number and starting time of each login session is marked in italics. The first column shows the lines processed by *csh* after history expansions were made. The current working directory is given in the middle column. Blank entries indicate that the directiory has not changed since the previous command line, and the "~" is *csh* shorthand for the user's home directory. The final column lists any extra annotations recorded. These include alias expansions of the line by *csh*, error messages given to the user, and whether history was used to enter the line. Long alias expansions are shown truncated and suffixed with "...".

Command line	Directory	Annotations
Session 1: Mon Feb 23 16:09		
mail	~	Alias: /usr/ucb/mail
Session 2: Thu Feb 26 11:05		
man mklib	~	
man -k mklib		
Session 3: Thu Feb 26 22:06		
cd 500	~	Alias: cd 500 ; set prompt = "[$cwd:t] #!...
ls	~/500	
vhide		Alias: echo — .hide directory — ; ls ...
c		Alias: /usr/ucb/clear
ls		
e assign9		Alias: emacs assign9
spitbol assign9		
e		Alias: emacs
spitbol assign9		History used
e		Alias: emacs
vhide		Alias: echo — .hide directory — ; ls ...
lpr .hide/graph.spit		
cd .hide		Alias: cd .hide ; set prompt = "[$cwd:t] ...
lpr graph.spit	~/.hide	
lpr symbol		
cd 500		Alias: cd 500 ; set prompt = "[$cwd:t] #!...
ls	~/500	
e assign9		Alias: emacs assign9
e		Alias: emacs
spitbol assign9		
ls		
e		Alias: emacs
spitbol assign9		History used
e		Alias: emacs
spitbol assign9		History used
e		Alias: emacs
ftp vaxc		
ls		
more assign8.spit		
e assign9		Alias: emacs assign9
spitbol assign9		History used
e		Alias: emacs
echo poop > file		
spitbol assign9		History used
e		Alias: emacs
spitbol assign9		History used
e		Alias: emacs
spitbol assign9		History used
e		Alias: emacs
ls		
e		Alias: emacs

spitbol assign9	History used
e	Alias: emacs
spitbol assign9	History used
e	Alias: emacs
spitbol assign9	History used
e	Alias: emacs
spitbol assign9	History used
ls	
rm assign8.spit *.bak *.ckp file	Alias: mv assign8.spit *.bak *.ckp file /...
ls	
e file1	Alias: emacs file1
cp file1 file2	
e file2	Alias: emacs file2
spitbol assign9	History used
e assign9	Alias: emacs assign9
spitbol assign9	History used
e	Alias: emacs
spitbol assign9	History used
e	Alias: emacs
more file3	
assign9	Error: system – permission denied
spitbol assign9	History used
e	Alias: emacs
ls	
more file3	
rm file3	Alias: mv file3 /.kill/
more file1	
spitbol assign9	History used
more file1	
e	Alias: emacs
spitbol assign9	History used
e	Alias: emacs
spitbol assign9	History used
e	Alias: emacs
spitbol assign9	History used
more file3	
more file1	
more file2	
e	Alias: emacs
spitbol assign9	History used
e merge.error	Alias: emacs merge.error
e assign9	Alias: emacs assign9
spitbol assign9	History used
more merge.error	
e	Alias: emacs
cat assign9	
∧Acat assign9	History used
	Error: execution – command not found
∧Acat assign9	History used
	Error: execution – command not found
cat assign9	History used
ls	

rm *.ckp *.bak merge.error file3		Alias: mv *.ckp *.bak merge.error file3 /...
ls		
script		
lpr typescript		
lpr typescript		History used
limits		

Session 4: Fri Feb 27 13:57

cd 500	~	Alias: cd 500 ; set prompt = "[$cwd:t] #!...
ls	~/500	
e assign9		Alias: emacs assign9
ls		
rm *.bak typescript		Alias: mv *.bak typescript /.kill/
ls		
rm merge.error		Alias: mv merge.error /.kill/
rm file3		Alias: mv file3 /.kill/
ls		
cd		Alias: cd ; set prompt = "[$cwd:t] #! ->...
script	~	
ls		
lpr typescript		

Session 5: Fri Feb 27 21:50

cd 510	~	Alias: cd 510 ; set prompt = "[$cwd:t] #!...
ls	~/510	
e rohl_machine.p		Alias: emacs rohl_machine.p

Session 6: Tue Mar 24 10:03

prmail	~	
who		
ls		
l		Alias: ls -asl ;
morembox		Error: execution – command not found
more mbox		

Session 7: Fri Mar 27 15:37

cd 510	~	Alias: cd 510 ; set prompt = "[$cwd:t] #!...
lpr rohl_machine.p	~/510	
lpr rohl_compiler.p		
spit		Error: execution – command not found
lpq		
s		Error: execution – command not found

Appendix C

Summary Statistics For Each Subject

The following pages list a few basic statistics observed for the subjects involved in the study. Each subject is identified by the name of his group and a number. For example, "novice-1" is the first subject of the Novice Programmer group. These names match the file names found in the publicly available trace data (Greenberg, 1988).

The statistics include each user's number of login sessions, the command lines entered, the different commands used, the *csh* errors noted, the times history was used, and the different directories accessed. For example, novice-1 entered 2457 command lines over 55 login sessions. Of those lines, 213 produced *csh* errors. History was invoked 37 times, 18 different directories were visited, and 67 different commands were used.

Novice subject number	Login sessions	Total command lines	Different commands	Errors noted by *csh*	Times history was used	Different directories used
novice-1	55	2457	67	213	37	18
novice-2	118	1267	22	58	0	11
novice-3	345	2337	26	93	0	1
novice-4	61	1919	32	123	0	4
novice-5	62	593	24	67	0	5
novice-6	74	871	23	44	0	1
novice-7	94	1039	38	51	98	11
novice-8	92	1822	13	19	0	3
novice-9	44	853	26	63	0	6
novice-10	64	1464	42	40	0	3
novice-11	59	256	26	21	2	1
novice-12	438	2436	19	210	0	2
novice-13	49	652	20	49	0	2
novice-14	156	3194	67	208	0	27
novice-15	79	1139	14	48	0	1
novice-16	16	256	12	25	0	1
novice-17	135	1194	23	59	0	1
novice-18	46	1088	15	38	0	1
novice-19	103	3401	59	363	7	4
novice-20	54	418	18	19	1	2
novice-21	44	849	22	42	48	3
novice-22	122	1893	43	51	0	3
novice-23	90	2138	30	72	0	2
novice-24	86	849	26	53	0	3
novice-25	169	2066	13	217	0	1
novice-26	87	1120	19	60	0	1
novice-27	71	1195	25	63	1	9
novice-28	123	2221	31	120	0	1
novice-29	94	1230	14	44	0	3
novice-30	78	946	20	28	0	3
novice-31	64	2073	27	102	0	7
novice-32	51	385	20	37	0	3
novice-33	199	3127	31	106	0	6
novice-34	123	1276	25	46	4	1
novice-35	90	1444	22	54	0	6
novice-36	141	3213	55	137	0	5
novice-37	88	1949	36	57	0	32
novice-38	109	839	12	17	0	2
novice-39	74	1107	34	51	0	3
novice-40	58	967	17	24	0	5

Novice subject number	Login sessions	Total command lines	Different commands	Errors noted by *csh*	Times history was used	Different directories used
novice-41	86	2317	15	51	0	1
novice-42	92	1068	31	33	0	3
novice-43	33	608	18	26	0	1
novice-44	59	1277	14	40	0	2
novice-45	54	651	17	16	0	1
novice-46	276	4163	120	372	112	58
novice-47	56	1316	19	78	0	3
novice-48	23	269	12	9	0	1
novice-49	23	723	20	31	0	1
novice-50	48	985	33	92	0	3
novice-51	42	480	20	20	0	2
novice-52	69	650	22	38	0	3
novice-53	98	1028	34	41	0	1
novice-54	38	683	19	56	0	10
novice-55	62	1662	25	40	6	2
experienced-1	137	3714	74	298	174	58
experienced-2	25	219	28	11	6	8
experienced-3	28	915	51	42	88	16
experienced-4	151	3776	59	123	2	29
experienced-5	283	4015	78	222	35	44
experienced-6	53	757	56	32	0	17
experienced-7	189	5857	139	612	67	100
experienced-8	134	2930	74	265	67	54
experienced-9	99	2351	99	136	86	25
experienced-10	25	446	45	26	1	18
experienced-11	98	1456	43	86	21	48
experienced-12	66	1763	70	92	28	17
experienced-13	49	1109	60	160	25	30
experienced-14	103	1810	60	153	23	27
experienced-15	14	225	21	12	0	32
experienced-16	41	795	33	22	24	22
experienced-17	85	2343	67	144	0	32
experienced-18	25	575	27	21	5	9
experienced-19	122	1807	84	88	163	20
experienced-20	180	4556	79	370	435	44
experienced-21	100	2394	76	83	157	54
experienced-22	149	2814	67	122	325	18
experienced-23	95	2306	70	119	189	18
experienced-24	114	3331	132	228	222	62
experienced-25	71	1465	63	89	11	19
experienced-26	30	679	33	66	0	22
experienced-27	219	1693	70	54	77	43
experienced-28	440	3893	93	60	78	24
experienced-29	71	2214	59	133	59	67
experienced-30	130	2028	64	110	82	18

Novice subject number	Login sessions	Total command lines	Different commands	Errors noted by *csh*	Times history was used	Different directories used
experienced-31	68	683	82	38	19	40
experienced-32	65	974	72	87	47	32
experienced-33	59	1292	55	65	83	14
experienced-34	116	1869	59	218	206	15
experienced-35	165	4272	77	169	28	40
experienced-36	60	1580	70	116	56	54
scientist-1	165	1856	105	111	54	43
scientist-2	198	2954	87	149	236	37
scientist-3	133	978	38	69	1	6
scientist-4	238	4507	112	320	178	114
scientist-5	197	1563	77	78	18	13
scientist-6	145	1103	61	49	33	46
scientist-7	13	366	49	28	0	25
scientist-8	61	842	39	51	0	5
scientist-9	256	4067	89	65	224	42
scientist-10	129	2024	63	120	77	96
scientist-11	38	205	24	13	0	1
scientist-12	105	2499	117	52	53	63
scientist-13	108	3593	45	118	357	25
scientist-14	202	3433	109	183	23	83
scientist-15	161	1429	94	81	200	30
scientist-16	74	326	31	29	0	5
scientist-17	95	569	33	38	0	1
scientist-18	144	2831	71	112	106	74
scientist-19	189	5584	65	240	6	62
scientist-20	225	2697	112	189	74	52
scientist-21	81	1762	82	134	50	102
scientist-22	132	750	45	39	0	12
scientist-23	324	3360	91	135	52	48
scientist-24	72	1494	41	55	0	5
scientist-25	415	3508	112	122	7	113
scientist-26	123	983	65	70	0	24
scientist-27	111	3817	97	85	102	79
scientist-28	111	765	64	26	20	17
scientist-29	134	2683	60	243	20	61
scientist-30	180	2129	77	123	186	56
scientist-31	65	250	20	20	9	3
scientist-32	78	601	36	20	0	9
scientist-33	24	325	16	12	0	3
scientist-34	204	2639	61	88	15	50
scientist-35	80	1049	46	29	23	22

Novice subject number	Login sessions	Total command lines	Different commands	Errors noted by *csh*	Times history was used	Different directories used
scientist-36	275	12056	181	566	488	202
scientist-37	121	4187	61	83	121	64
scientist-38	131	3775	92	168	48	113
scientist-39	119	1753	76	77	173	40
scientist-40	348	4605	66	98	0	42
scientist-41	204	2037	49	36	0	5
scientist-42	298	6068	133	644	6	158
scientist-43	108	3106	86	101	0	37
scientist-44	72	1543	62	84	12	16
scientist-45	40	862	76	59	17	17
scientist-46	294	2551	92	110	80	89
scientist-47	75	1229	67	81	9	61
scientist-48	76	819	27	43	0	2
scientist-49	105	1448	108	97	138	46
scientist-50	138	1496	75	225	219	18
scientist-51	74	910	43	67	0	51
scientist-52	263	7705	121	299	231	93
non-progs-1	95	1622	61	59	0	7
non-progs-2	53	454	16	15	0	2
non-progs-3	85	1265	38	15	9	7
non-progs-4	133	5050	70	161	18	89
non-progs-5	77	244	8	11	0	1
non-progs-6	23	177	17	7	0	2
non-progs-7	80	1231	53	54	3	9
non-progs-8	23	239	32	13	28	14
non-progs-9	73	357	34	23	4	3
non-progs-10	32	495	36	20	0	21
non-progs-11	281	1848	27	61	0	17
non-progs-12	24	216	19	26	0	4
non-progs-13	30	487	10	5	0	1
non-progs-14	17	201	9	4	1	3
non-progs-15	78	571	15	28	0	2
non-progs-16	46	821	32	26	18	11
non-progs-17	61	848	19	65	0	1
non-progs-18	97	1403	22	64	0	2
non-progs-19	77	175	15	7	0	2
non-progs-20	137	4042	81	124	165	30
non-progs-21	25	132	5	7	0	1
non-progs-22	151	1567	39	56	48	8
non-progs-23	89	1294	47	48	0	5
non-progs-24	35	542	25	34	0	1
non-progs-25	76	327	9	18	3	1

Appendix D

The Uniform Recurrence Distance Distribution

This appendix considers the case when the probability of a user's submission matching a previous one is equiprobable over the history list. As the length of the history list grows with the number of submissions, the distribution is expected to be skewed toward the smaller distances which have been around longer. More formally, the uniform recurrence distance distribution is defined as the probability distribution of a recurrence over distance after n submissions, when recurrences are equiprobable over a growing history list. This appendix derives the equation describing its shape. I will argue that although the distribution's skewness is an artifact included in the observed UNIX recurrence distributions, its effects are minor and can be ignored.

The probability of a particular recurrence over the history list is derived[1]. Consider a user who is about to submit their nth submission to the system. First, the probability is calculated that this submission is not a recurrence of a previous one, or that it is a recurrence at a particular distance d, where $d < n-1$ since the size of

[1] The history list simulated here is similar to a list with duplicates saved only in their latest position of occurrence (Section 6.1.2).

submission	is not a recurrence	does recur at a distance of 1	2	3	4	…	n
1	1	0	0	0	0	…	0
2	$1-\mathcal{R}$	$\mathcal{R}/1$	0	0	0	…	0
3	$1-\mathcal{R}$	$\mathcal{R}/2$	$\mathcal{R}/2$	0	0	…	0
4	$1-\mathcal{R}$	$\mathcal{R}/3$	$\mathcal{R}/3$	$\mathcal{R}/3$	0	…	0
5	$1-\mathcal{R}$	$\mathcal{R}/4$	$\mathcal{R}/4$	$\mathcal{R}/4$	$\mathcal{R}/4$	…	0
⋮	⋮	⋮	⋮	⋮	⋮	…	⋮
n	$1-\mathcal{R}$	$\frac{\mathcal{R}}{n-1}$	$\frac{\mathcal{R}}{n-1}$	$\frac{\mathcal{R}}{n-1}$	$\frac{\mathcal{R}}{n-1}$	…	$\frac{\mathcal{R}}{n-1}$

Table D.1: Calculating probabilities for the uniform distance distribution

a strict sequential history list is $n-1$ submissions. When $n=1$, there is no history list, and the item cannot be a recurrence. When $n>1$, the recurrence probability $\mathcal{R}$ (now expressed as a fraction) must be shared equally between the $n-1$ items on the history list, since by assumption each item is equiprobable. Hence $\mathcal{R}_d^n$, the probability of a recurrence at a given distance d for the nth submission, is $\mathcal{R}/(n-1)$. Table D.1 illustrates this situation, where each row shows the number of submissions, the probability that it is not a recurrence, and $\mathcal{R}_d^n$ for particular distances. For example, if $\mathcal{R}=0.75$ and the fifth submission is being entered, there is a 0.25 chance that it is not a recurrence, and a $0.75/4=0.187$ chance that it recurs at one of the four possible distances.

The next step calculates $\mathcal{R}_D^n$, accumulated over all previous n submissions up to and including the nth one. $\mathcal{R}_D^n$ is the probability of an item recurring at particular distances d for a *growing* history list, which is the averaged probability of all $\mathcal{R}_d^n$ found in the column for a particular distance d (Table D.1).

$$\mathcal{R}_D^n = \frac{1}{n}\sum_{i=d}^{n-1}\frac{\mathcal{R}}{i} = \frac{\mathcal{R}}{n}\sum_{i=d}^{n-1}\frac{1}{i}$$

If the values of all $\mathcal{R}_D^n$'s for every distance possible were calculated and averaged over n, and the chance that a submission is not a recurrence is included, the following

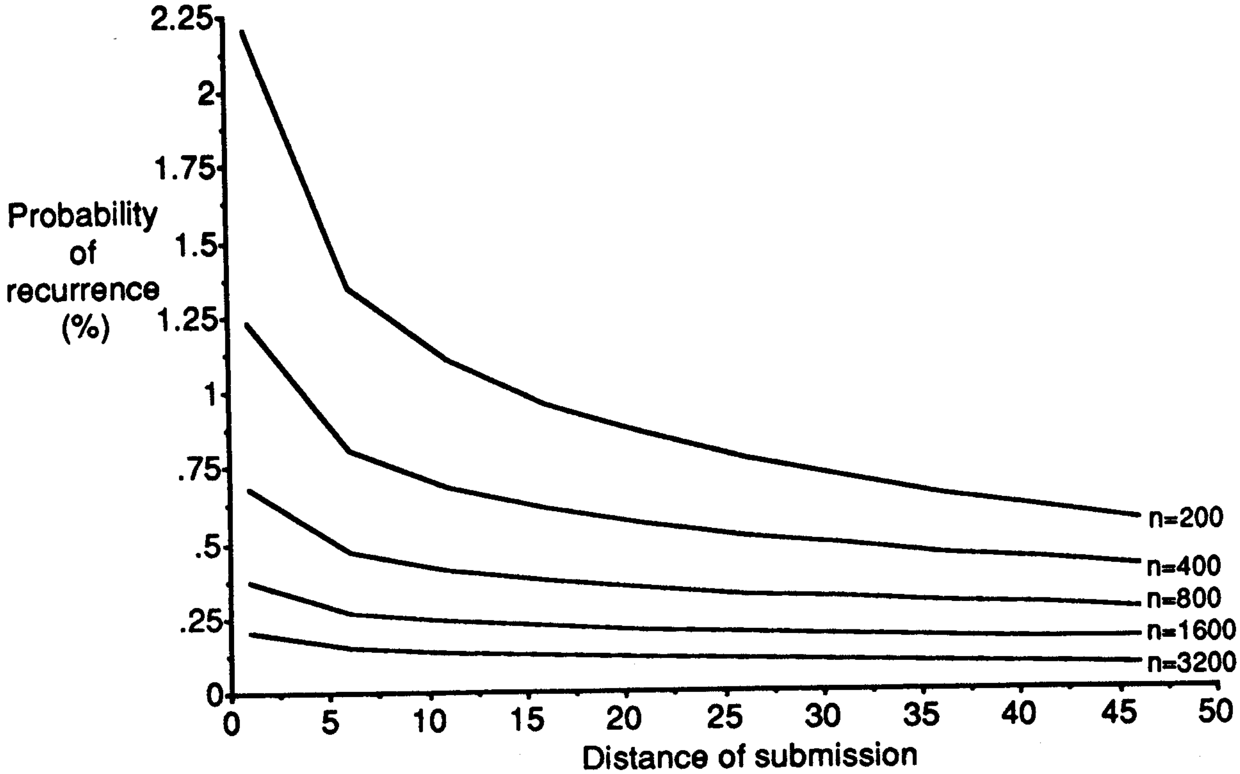

Figure D.1: The uniform distance distribution for different values of n

balanced equation is produced:

$$1 = \frac{1}{n}(1 + \sum_{d=1}^{n-1} (\mathcal{R}_D^n + 1 - \mathcal{R}))$$

Informally speaking, each row of Table D.1 sums to 1 since n rows are added and then divided by n.

The distribution of $\mathcal{R}_D^n$ with values of d ranging from 1 through 50 is illustrated in Figure D.1. The recurrence rate R was set to 0.75, the observed population average of our study. Each line represents different values of n between 200 through 3200. Although $\mathcal{R}_D^n$ always decreases as d increases, the rate of decrease is smaller as n gets larger.

Should the conditioned distributions described in Chapter 6 be normalized to take into account the decreasing probabilities over distance? If they were, the corrected observations would reflect a true estimate of the recurrence distribution regardless of the size of n, and the differences between the actual number of activities recorded by each subject would not bias the results. However, this has not been done for the following reasons. First, around 2000 activities were entered on average by an expert subject. As seen by Figure D.1, the differences in values between $\mathcal{R}_D^n$ are quite small at this range. Second, the value of $\mathcal{R}_D^n$ for small distances is negligible when compared to the corresponding observed recurrences. Third, it is not clear how useful a normalized estimate would be, for people *are* operating on history lists of finite length. The slight effect of normalization on the recurrence distribution would not alter the conclusions of Chapter 6.