decomposable systems. This analysis is an example of how this distinction can be used to dissect models of computing systems into subsystems which can be (i) evaluated separately and (ii) represented by a few aggregative variables whose interactions can be analyzed at a higher level of aggregation. The degree of approximation necessitated by this approach remains known and is probably the price we have to pay to evaluate complex systems.

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Operating Systems — R. Stockton Gaines, Editor

A Large Semaphore Based Operating System

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The paper describes the internal structure of a large operating system as a set of cooperating sequential processes. The processes synchronize by means of semaphores and extended semaphores (queue semaphores). The number of parallel processes is carefully justified, and the various semaphore constructions are explained. The system is proved to be free of "deadly embrace" (deadlock). The design principle is an alternative to Dijkstra's hierarchical structuring of operating systems. The project management and the performance are discussed, too. The operating system is the first large one using the RC 4000 multiprogramming system.

Key Words and Phrases: cooperating processes, operating system, semaphores, semaphore applications, queue semaphores, deadlock, deadly embrace, hierarchical structuring, multiprogramming, operating system structure, asynchronous structuring, buffering, parallel processes, synchronizing primitives, reentrant code, RC 4000, project management, time schedule, debugging, project planning, project scheduling, reliability, program proving, coroutines, correctness, program maintenance, software paging

CR Categories: 4.30, 4.31, 4.32, 4.42, 4.43, 5.24

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1. Introduction

1.1 Facilities of Boss 2

The operating system Boss 2 was developed for RC 4000 in the period 1970 to 1972. Boss 2 is a general purpose operating system offering the following types of service simultaneously: batch jobs, remote job entry, time sharing (conversational jobs), jobs generated internally by other jobs, process control jobs. The system can at the same time be part of a computer network, allowing jobs to transmit files to CDC 6400 and Univac 1106/1108.

Boss 2 handles a maximum of 50 terminals, various types of backing stores and magnetic tapes, printers, readers, punch, plotter, and various process control devices. The resources are available for all types of service. Boss has a dynamic priority system based on swapping and updates an estimate of the job completion times taking into account all resources demanded by the jobs. This estimate is available from the terminals. All the facilities can be used with a core store from 32 k words (of 24 bits) and a disk of 2 M words.

Performance measurements have been made on a service center configuration with 20 terminals, 64 k words of core store, and a small added drum. The jobs are production runs and debugging of medium and large data processing programs. During the six busiest hours, the cpu-utilization is 40–50 pct used by jobs, 10–20 pct by the operating system and the monitor. The average operating system overhead per job is 3 sec—including nonoverlapping I/O transfers in the operating system. The response time to simple on-line commands like editing is negligible (less than 0.5 sec).

During the first year of operation, the system typically ran for weeks without crashes. Today it seems to be error free.

1.2 The RC 4000 System Without Boss 2

Boss 2 runs under an extended version of the *Monitor* (Nucleus) described in [2, 3, and 16]. The principles of the Monitor may be outlined as follows.

The Monitor is a set of procedures which make the computer appear as if it were executing several programs at the same time. The sequential execution of such a program is called a *process*. Some of the processes are built-in *drivers* (external processes), some of them are *job processes* executing a sequence of user defined programs (job steps), and some of them are *operating systems*.

Any two processes can communicate and synchronize by means of *messages*. Each process owns a set of message buffers in the protected Monitor and it has a message queue in which it can receive message buffers sent to it from other processes (Figure 1). It can call a Monitor procedure asking to wait until a message buffer is in this queue, and it can return a message buffer to the sender (send answer). Two other Monitor procedures allow it to send a message to another process

Fig. 1. Process communication by means of messages. In the example, B is the sender of a message to the receiver A. Sender and receiver are identified by a process name of at most 11 characters. Return parameters are underlined.

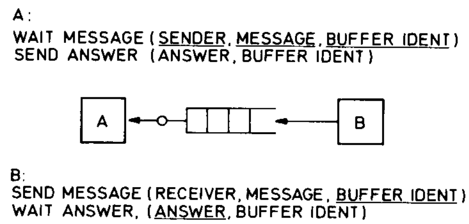


Fig. 2. Processes and coroutines. Processes are implemented by the RC 4000 Monitor. Coroutines are implemented inside the single Boss process. The set of coroutines is idealized.

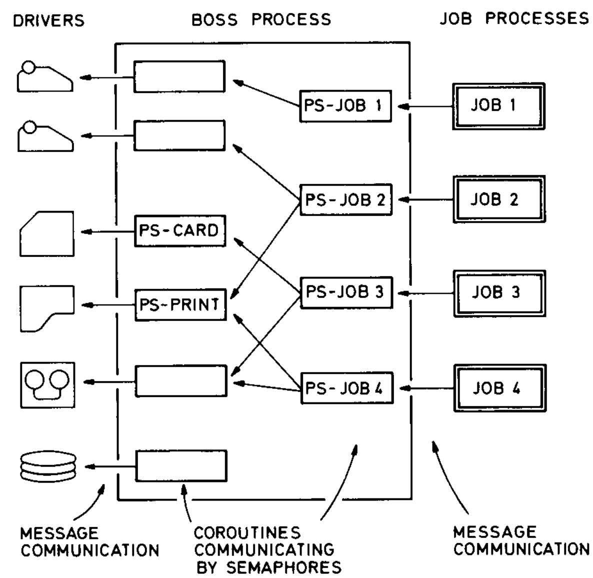
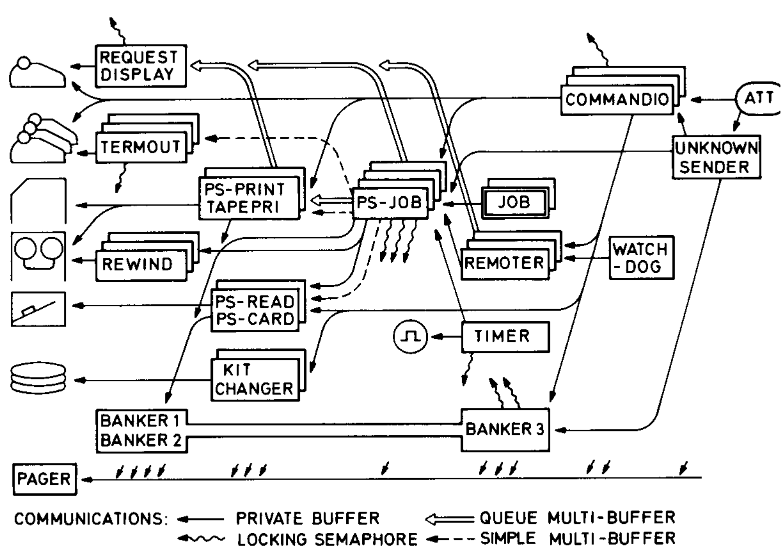


Fig. 3. All coroutines of Boss 2 and their communication. Some peripheral devices are shown, too.



and wait for an answer to be returned. A further Monitor procedure—essential for implementation of operating systems—allows a process to wait for the first coming message or answer (wait event).

A process owns a set of resources like working store and message buffers. It can use a part of these resources to create another process (a child) running in parallel with the creator (the parent). Later the parent can remove the child and get the resources back. A process which is an operating system creates job processes in this way.

The pragmatic rules for communication job/operating system and job/drivers were developed from 1969 to 1970, that is, before any advanced operating system was planned. In this early period a lot of compilers and utility programs were developed, and for compatibility reasons Boss had to follow the old pragmatic rules.

During the period from 1969 to 1972 the computer was mostly operated with an extremely simple operating system which handled core resident job processes only. The creation and removal of job processes was always ordered manually and executed immediately or rejected (i.e. no job queue existed in the computer). A job process could send two kinds of messages: input/output messages to the drivers and parent messages to the operating system. The input/output messages asked for operations very close to the hardware, like transfer of a data block or position of a magnetic tape. Input/output strategies and error recovery were mostly handled by the user programs and the library procedures. The parent messages asked for a variety of functions like mount a magnetic tape, mount a paper tape, terminate the job, abort the job step in at most x seconds, print an operator message.

The simple operating system simply printed all parent messages on a console without trying to understand them. Although it was quite convenient to handle tape mounting and paper tapes in this way, the method was unsuited for handling files on disk (open file, create file, etc.). A major fault in the early design was that file handling was not communicated as parent messages —with automatic handling in the simple operating system. Instead a special set of monitor procedures was supplied, which did not even use the message mechanism. As a result, later operating systems could not "catch" the file handling requests, and disk allocation strategies became limited by the monitor.

1.3 The Place of Boss 2 in RC 4000

These were the conditions upon which we started the development of Boss 2. We would not change the existing software unless strictly necessary. However, we soon found it necessary to modify and extend the file handling procedures in the monitor, and this project developed in parallel with Boss 2 [16].

Figure 2 shows the process Boss which executes the Boss 2 program. The job processes are children of Boss. Boss receives messages from the job processes and sends the answer when the requested operation is completed. Of course the jobs send all parent messages to Boss, but some input/output messages are also sent to Boss, because Boss simulates some devices and behaves like a set of drivers toward the job. The devices simulated are very slow devices requiring spooling and devices difficult to share (low speed terminal, paper tape reader, printer). The job sends input/output messages directly to the drivers for fast devices like disk and magnetic tape.

Boss sends messages to various drivers either to complete the device simulation (terminal, reader, printer) or to execute a parent message (reading a magnetic tape label in connection with the parent message "mount magnetic tape").

Inside Boss, a set of parallel activities is going on: one activity synchronized to each job and one synchronized to each peripheral device (i.e. to the driver). These activities will, in principle, communicate with each other as shown in Figure 2. Each activity could have been implemented as a process under the monitor, but in an unsuccessful project (Boss 1) we had learned that processes and messages were completely unsuited for the purpose.

The major problem is that each process has its own message queue. For instance it is not possible to let a message queue represent a pool of free records—common to several processes—because only one process can get messages from the queue. For the same reason, Dijkstra's semaphore construction for critical regions cannot be made directly with messages. It would be possible to solve these problems by introducing an administrator process, but its logic would be complicated.

Other problems are that RC 4000 processes are very difficult to make reentrant, and they cannot readily share code or data tables, especially when swapping or paging is used.

Finally, only 23 processes plus drivers can be created in RC 4000, and we needed more than a hundred parallel activities inside Boss. So in all cases we would have to simulate more parallel activities inside one process.

The solution we chose was another level of multiprogramming running inside the single Boss process. The monitor of this "multiprogramming system" is called the Boss 2 Central Logic, the parallel activities are called coroutines, and the communication and synchronization is done by means of simple semaphores and queue semaphores as explained in the sequel. The coroutines run in a virtual memory simulated by the Central Logic and with the core store areas of the job processes considered special pages. The synchronization to the surroundings (replacing interrupts in a conventional multiprogramming system) is handled by means of the monitor procedure "wait event," which allows the Central Logic to wait for the first answer or message (the first "interrupt").

Below we will discuss the coroutines and show why the Deadlock problem changes the idealized picture of Figure 2 to the actual one in Figure 3.

The design is shown to be governed by the parallel activities (one synchronized to each job and one synchronized to each peripheral device). A hierarchical structure of the parallel activities is imposed afterward in order to prevent Deadlock.

2. Coroutines and Semaphores

2.1 Basic Coroutine Scheme

Each coroutine of Boss will perform an activity with a speed determined by a peripheral device or a job process. Typically, the following activities will be in progress simultaneously:

a. Printing data from the disk to the line printer—as fast as allowed by the printer (performed by the coroutine "ps-printer").
b. Reading data from card reader to the disk—as fast as allowed by the reader and the operator (coroutine "ps-card").
c. Communicating with a user terminal about editing, file listing, etc. (coroutine "commandio 1").
d. Communicating with a second user terminal (coroutine "commandio 2").
e. Performing a user job, i.e. handle the messages sent from the job process to Boss (coroutine "ps-job 3").
f. Performing a second user job (coroutine "ps-job 4").

The coroutines may be thought of as parallel processes, the only essential difference being the rigid scheduling of cpu-time.

The coroutines use only a little cpu-time and disk time, and as a result they need not delay each other. Of course, an activity like (a) above may run out of data to be printed, and then it will have to await the arrival of new data from activities like (e) and (f).

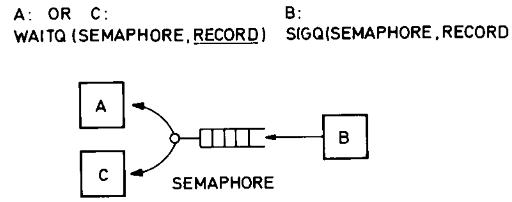
In general, the algorithm executed by a coroutine follows this *basic scheme:*

Step 1. Wait for a request to do some work.
Step 2. Send a finite number of requests to other coroutines or drivers.
Step 3. Answer the request of Step 1.
Step 4. Send a finite number of requests to other coroutines or drivers.
Step 5. Go to Step 1.

For a ps-printer (activity (a)), Step 1 waits for a request to print some data. The requests are sent from other coroutines by means of semaphores, and in busy periods several requests may be queued up. Step 2 sends requests to the printer driver in the form of messages and awaits the answers. When there are troubles with the printer, Step 2 may also send requests to the operator. Step 4 is blind.

For a ps-job (activity (e) and (f)), Step 1 waits for a

Fig. 4. Process (or coroutine) communication by means of queue semaphores. The queue semaphores have no fixed relation to the processes, and in principle any process may wait for or signal (send into) the queue. When A or C has received a record, they will later return it to a separate queue of free records (not shown). B can then get a new record from this queue.



message from the job process or a request from the operator's or user's terminal. Steps 2 and 4 depend on the actual request, and they may involve requests to a variety of coroutines and drivers.

In general, a coroutine waits for a request in Step 1 and for answers to requests in Steps 2 and 4. This is accomplished by calling the Central Logic, which returns to the coroutine in case the request or answer is ready. If it is not ready, the Central Logic returns to another coroutine which is ready to run, or it calls the monitor function "wait event." Section 4.2 elaborates on this topic and on the use of reentrant code to implement identical activities like (e) and (f).

The size of the coroutine algorithms varies considerably: "rewinder" is just 30 instructions, "ps-job" and "commandio" are several thousand. Thus coroutines are not a partition of the code into manageable pieces. Rather they reflect the external requirements to parallel action. Notice, that if we want the basic scheme above and want to run all peripherals and all jobs in parallel, we need *at least one coroutine for each peripheral and each job.*

2.2 Queue Semaphores

The communication and synchronization between coroutines is done by means of queue semaphores and simple semaphores. A *queue semaphore* is an abstraction which represents a queue of records or a set of coroutines waiting for records to be put in the queue (Figure 4).

Two procedures of the Central Logic handle the queue semaphores:

waitq(semaphore, record):

The procedure "wait queue" removes the first record from the queue represented by the semaphore. A pointer to the record is returned to the calling coroutine. If the queue is empty, the calling coroutine is suspended—waiting until a record is available in the queue.

sigq(semaphore, record):

The procedure "signal queue" inserts a record (specified by a pointer) into the queue of the semaphore. If coroutines are waiting for records in the queue, one of them will be activated and it will run later.

The main difference between queue semaphores and messages is that a queue semaphore does not belong to a single process (or coroutine). In principle, any coroutine may wait for or signal any queue semaphore. Another difference is that the records may have any length, while the message buffers are restricted to eight words.

When coroutines communicate, two semaphores are involved. One semaphore holds the requests, the other the answers.

As an example, consider the communication between a ps-job and a ps-printer. The requests are queued by the semaphore "print queue," and a request record specifies that a certain file should be printed. The free records are queued by the semaphore "print free." Now the ps-job uses the basic scheme in this way:

Step 1. Wait for a request from job, operator, or user.
Step 2. **if** request is print a file **then**
        begin *waitq*(print free, record);
          store print request in record;
          sigq(print queue, record);
        end;
Step 3. . . .

The ps-printer uses the basic scheme in this way:

Step 1. *waitq*(print queue, record).
Step 2. print the file using send message and wait answer.
Step 3. *sigq*(print free, record).
Step 5. **goto** step1;

Note that these algorithms cause waiting in the proper way. When no free records are available, the ps-job will wait on "print free" in Step 2. When no requests are in the queue, the ps-printer will wait on "print queue" in Step 1.

If several printers exist, each of them is served by its own ps-printer. Any printer may print a file. This is obtained automatically if "print queue" is common to all ps-printers. As long as "print queue" is nonempty, all printers will be busy. This simple implementation of parallel request processing is difficult to obtain with most other communication methods. For instance, messages are completely unsuited for that purpose.

The communication principle corresponds to the beautiful, symmetrical producer-consumer algorithm of Dijkstra: the ps-job consumes free records and produces requests. The ps-printer consumes requests and produces free records. The principle can also be thought of as a generalization of the conventional double buffer scheme to *multi-buffers*. (A record corresponds to a buffer.) In Figure 3, 4 double arrows show such multi-buffer communication based on queue semaphores. The arrow shows the direction of the request.

2.3 Simple Semaphores

Simple semaphores were introduced by Dijkstra [5, 6]. They resemble queue semaphores, but the queue is not represented explicitly. Only a count of the records in an abstract "queue" is kept track of.

Thus, simple semaphores can be used to implement queues where the records are linked in a user defined manner or where the record does not contain essential information.

Simple semaphores are handled by the following two procedures of the Central Logic:

wait(semaphore)
sig(semaphore)

It is assumed that coroutines follow the discipline of handling a semaphore either with *waitq/sigq* exclusively or with *wait/sig*.

As an example, consider the handling of output from a job to the terminal. Each request consists of one word to be printed (3 characters), and an ordinary queue would be too cumbersome. Instead the ps-job and the "termout" agree to use a backing store area in a cyclical manner. Two simple semaphores represent the number of full and free words, and the algorithms look exactly like those originally proposed by Dijkstra. Multi-buffers implemented in this way appear as dotted arrows in Figure 3.

As another example, we will elaborate on the parallel printers of Section 2.2. In practice we want to sort the files according to paper type (one copy, two copies, special forms, etc.) in order to minimize paper changing. So we use one queue for each paper type and a common abstract queue representing the total number of print requests. The abstract queue is implemented by a simple semaphore "common print." Now the ps-job sends a print request in this way:

Step 2. *waitq*(print free, record);
        store print request in record;
        sigq(paper type queue, record);
        sig(common print);

The ps-printer proceeds like this:

Step 1. *wait*(common print);
        if queue of current paper type is empty **then**
        begin select a non-empty paper type queue (at least one exists) according to some strategy;
          current paper type := queue selected
        end;
        waitq(current paper type, record);

Step 2. . . .

Note that selection of current paper type is a critical region which should be executed by at most one ps-printer at a time. Otherwise two ps-printers could decide to wait for the same paper type queue, which happened to contain only one request.

2.4 Critical Regions

A critical region is a part of an algorithm which updates variables common to several processes (or coroutines). If a certain relation is to be maintained between the common variables, one process must complete the critical region before another process can enter a critical region working on the same variables.

A sound solution is to use a queue with one record which contains the common variables. When a process wants to update the variables, it gets the record by means of *waitq*. After the updating it returns the record to the same queue by means of *sigq*. If other processes want to update the variables meanwhile, they will be suspended when executing *waitq*.

Because only one record is involved, its address may be known to all processes, and a simple semaphore may replace the queue semaphore. This was the solution described by Dijkstra, and it is also used in Boss. The corresponding *locking semaphores* are shown in Figure 3 as waved arrows.

The special coroutine scheduling of cpu-time allows a simpler handling of critical regions in many cases: the Central Logic can only pass control to another coroutine when a coroutine explicitly waits. As a result, critical regions without embedded waiting can be handled without semaphores. This simplifies programming in many cases, for instance in the printer case of the preceding section.

2.5 Private Buffers and Messages

A special case of multi-buffer communication is frequently used. Each sender of a request has his own record, and he wants the answer to be returned through his private semaphore, which may be simple. The private semaphore is specified in the request. The sender uses the basic scheme in this way.

Step 2 or 4. *sigq*(request queue, private record);
wait(private answer semaphore);

Because all the algorithms are loops, you may think of the scheme in a rotated form with *wait* preceding *sigq*. Then it looks again like the producer-consumer algorithm.

The receiver uses the basic scheme in this way:

Step 1. *waitq*(request queue, record);
Step 3. *sig*(record [private answer]);

This private buffer communication corresponds exactly to the message/answer communication with the drivers. In Figure 3 they are all represented by normal arrows.

3. Deadlock and Hierarchical Structuring

3.1 Absence of Deadlock, Basic Proof

We can prove the absence of Deadlock in Boss by proving that no coroutine waits forever when it has useful work to do.

In the basic scheme of Section 2.1 we can distinguish two kinds of waiting. Waiting in Step 1 for a request is *idle waiting*. If the coroutine waits forever here, it does no harm as it then has no work to do. Waiting in Step 2 or 4 is *answer waiting*. If the coroutine waits forever here, we have a Deadlock as it will not be able to process the requests.

In Figure 3 all requests go from right to left, and we can then prove by induction that all requests are processed in a finite time: All "coroutines" to the extreme left are drivers which by definition complete their operation in a finite time (at least if they are handled properly by the operator). Now it follows that coroutines in column 2 from the left terminate their Steps 2 and 4 in a finite time, and hence they produce the answer (Step 3) in a finite time. If the request queue is implemented as First-In-First-Out or any other kind of fair scheduling, we have then proved that all coroutines in column 2 answer a request in a finite time. We can now proceed to column 3, and so on, until absence of Deadlock has been proved for every coroutine.

Note that data may flow in the same direction as the request (e.g. for a printer) or in the opposite direction (e.g. requests for paper tape input).

In the next section we will tackle the Deadlock problems originating from locking semaphores and other deviations from the basic coroutine scheme.

The requirement that "all requests go from right to left" is a very strong design criterion. In some cases it has caused a coroutine synchronized to a single peripheral device to be split up in two.

This has happened with terminals which have a two-way initiative: The job may request input or output from the terminal, and this is handled by the coroutine "termout." The user may also request actions from the system while his job is running. For instance he may want a print out of the job state or the job queue, or he may ask the system to kill the job. This is handled by the coroutine "commandio." As the two coroutines share the terminal, they use a locking semaphore to get exclusive terminal access during a conversation.

In Figure 2 the system is shown with only one coroutine to handle a terminal, but then we have requests in both directions to the ps-job. As a result we would risk Deadlock, because the terminal coroutine could wait for an answer from the ps-job, while the ps-job waited for an answer from the terminal coroutine. None of them would then be able to process the request from the other.

Also magnetic tape stations have a two-way initiative, because Boss may try to rewind the tape (the coroutine "rewinder") while the operator unloads it and mounts a new tape (the coroutine "remoter").

Because all communications are symmetrical producer-consumer algorithms, the direction of the request may seem rather arbitrary. However, it is well defined from a semantic point of view. For instance if the ps-printer does not get a request, it is because no printing is needed. But if it does not get an answer, printing is needed but not carried out.

In some cases we could imagine a system with a reversed request direction. For instance, we could try to construct a system where the tape reader issued a request whenever a paper tape was inserted. We could then try to prove that all tapes were loaded sooner or later. In the present system we can only prove that a job requesting a tape will be able to progress sooner or later.

3.2 Absence of Deadlock, Special Cases

The basic coroutine scheme does not explicitly mention the use of locking semaphores to control critical regions. So we will have to prove separately that no coroutine waits forever to enter a critical region.

When a coroutine has two or more nested critical regions, all other coroutines must use the same sequence of nesting. Then the entering into an inner critical region cannot be delayed endlessly by another coroutine being in the same critical region.

If a coroutine awaits an answer inside a critical region, the producer of the answer may not require entrance to the same critical region. This rule propagates recursively, as the producer of the answer may not even await an answer from another coroutine using the same critical region.

Thus the locking semaphores create two rules to be followed (and proved) in each coroutine.

Next we will discuss a more serious deviation from the basic coroutine scheme: In some cases a coroutine does not produce the answer in Step 3 until it has gotten other requests in Step 1. The proof methods used here vary from case to case.

As an example consider the coroutine "request display," which prints operator requests and maintains a list of operator requests which have not yet been completed. Operator requests are messages like "mount magnetic tape" or "change paper." The list of incompleted requests can be printed on demand.

The request display receives two kinds of requests. One is "insert," which specifies an operator request to be printed and kept in the list. This request is not answered in Step 3. The other kind is "delete," which specifies that a request should be deleted from the list—presumably because the operator action is completed. In this case Step 3 answers both the delete request and the earlier insert request.

The proof that all requests are eventually answered involves two rules. First, the operator is supposed to honor a request in a finite time and this must cause a "delete" to the request display. The second rule imposes a limit on the number of "insert" requests which a coroutine may have pending. This limit is one for each ps-printer, ps-reader, and ps-job with addition of one for each tape station (to be used either by the ps-job or the remoter). The limit is zero for all other coroutines. If these rules are followed by every coroutine, we prevent Deadlock simply by making a sufficiently large pool of free request records.

As a more important example consider the coroutine "Banker," which allocates resources to the jobs. When a coroutine wants to reserve or release resources, it sends a private buffer (Section 2.5) to the Banker stating the set of resources involved. It gets the answer to a release request immediately, and the answer to a reserve request when the resources are available. Again, the Banker may skip the answer in Step 3 until more resources have been released. The proof in this case is somewhat complicated and assumes that the maximum set of resources needed by a job is stated at job start. The allocation algorithm and details of the proof are given in [11].

We should mention that the Banker is the only coroutine not synchronized to a job or a peripheral device. In fact the Banker is superfluous as a coroutine, and it could be replaced by a reentrant procedure which is called by any coroutine wanting to reserve or release resources for a job. The solution would then become the "private semaphore" scheme described by Dijkstra [5]. Later, Dijkstra has proposed the private buffer scheme actually used in Boss (the "Secretary" of [7]).

During the debugging we met some Deadlocks caused by trivial programming errors (e.g. waiting for a wrong semaphore) and one Deadlock caused by violation of the second rule for locking semaphores (easily corrected by splitting the critical region in two).

3.3 Hierarchical Structuring and Coroutine Structuring

The basic proof of Deadlock absence is equivalent to that of Dijkstra and Habermann [5 and 9]. Especially, the idle waiting in Step 1 corresponds to their "homing position."

If we wish it, we could regard the set of coroutines as structured in a hierarchy like Dijkstra's. Each column of coroutines would then correspond to a level of the hierarchy. But this is not the way things developed.

A hierarchical structuring is usually invented during the construction process. This we have done inside each coroutine, by arranging the program in nested parts and procedures in the usual manner.

Contrary to this, the structuring into coroutines is mainly determined by the external requirements. The general rule seems to be this: *Make one coroutine (or process) for each independent stream of external events.* In our case, each job process and each peripheral device supplies an independent stream of events. Devices with a two-way initiative supply two independent streams of events and are consequently handled by two coroutines. (The only exception in Boss is the Banker, as discussed in Section 3.2.) The structuring into columns comes later and serves to guide the proof of Deadlock absence.

The author has used this structuring principle with equal success in later projects like message switching and remote process control. One additional rule has turned up: Assume that the processing of a critical event stream requires much cpu or disk time. Then two coroutines with an intermediate multi-buffer should be used in order to overlap event receiving and processing: one coroutine which receives the external events and one which spends the cpu or disk time. The latter coroutine may as well serve several coroutines of the first kind.

4. Implementation Principles

4.1 Virtual Store

The total space occupied by coroutine algorithms, records, and other variables is much too large for the core store. Instead, we implemented a virtual store based on software paging.

Each word in the virtual store is identified by a 22-bit virtual address. The lower range of addresses corresponds to resident parts of the virtual store—with the virtual address being the hardware core address. The middle range of addresses corresponds to virtual store parts on drum—which are transferred to the core store upon demand. The high range of addresses is similar, but corresponds to virtual store parts on a disk.

The virtual store is divided in *sections*, where each section is a full number of physical blocks on the device (block size equals 256 words of 24 bits). Whenever a word of the virtual store is needed and it is not in the core store, the entire section containing the word is transferred. In practice we consider the virtual store as divided in *pages* of consecutive words. A page is always allocated inside a section to allow fast addressing of the entire page after an initial page access. Several small pages can be allocated in a one block section, whereas large pages occupy a section each.

4.2 Coroutines

Each coroutine is represented by an 8-word coroutine description which is resident in the core store. One of the words is used as a link, either to a semaphore (when the coroutine waits for it), to the pager queue (when the coroutine waits for page transfers), to the active queue (when it waits for cpu-time), or to the answer queue (when it waits for a driver answer). One word is used for identifying the driver answer waited for, or for working during operations on queue semaphores. Five words contain virtual addresses, which represent pages to be held in the core store while the coroutine uses the cpu. A bit in each of these *page description* words shows whether the page is modified by the coroutine so that it should be written back. The first page description always represents the *code page* in which the current coroutine algorithm is found. The last word represents the return address to the coroutine. The address is relative to the beginning of the code page.

When a coroutine runs, the first five words of its current code page contain the absolute core addresses of the five pages of its coroutine description. In this way the code can easily access data in the five pages. Note that the page allocation can only change when the coroutine explicitly calls the Central Logic. The coroutine gets access to other pages by changing the coroutine description and then calling the Central Logic. In this case other coroutines may run during the page transfers.

Reentrant coroutines are handled by allocating all the variables in pages other than the code page. Thus, two reentrant coroutines may run with the same code page but different variable pages.

4.3 Semaphores

Each semaphore is represented by 3 core resident words. One word is a count of the number of records or —when negative—the number of coroutines waiting on the semaphore. Two words point to the beginning and the end of the record queue (or the queue of coroutine descriptions waiting on the semaphore). This semaphore representation is rather clumsy and could be replaced by a one-word representation as shown in [15].

The records of a queue are pages in the virtual store —linked together through their first word.

4.4 Paging Method

As outlined above, demand paging is used. Of particular interest is the fact that several pages may be needed simultaneously, and any page size (really section size) may be used.

The core resident pager coroutine transfers pages upon request from other coroutines. It will complete all page transfers for one coroutine before it handles the next coroutine in its request queue. It awaits the disk and drum transfers as all other coroutines by means of an entry to the Central Logic, thereby allowing the execution of other coroutines with all their current pages in the core store.

The pager coroutine and the Central Logic maintain a priority for each page in the core store. The priority represents a least-recently-used strategy, but with regard to pages presently used as I/O buffers or job processes. The latter type of pages will have a very high priority until the answer arrives or the job process is swapped out by the Banker. The pager tries with a simple strategy to allocate all demanded pages in low priority parts of the core store.

5. Project Plan and Time Schedule

5.1 First Project Plan

The design of Boss 2 was started at Regnecentralen, Copenhagen, in August 1970 by Klavs Landberg, Per Mondrup, and the author. In October 1970 we completed the *project specification* as an internal report. That part of the report which specified the facilities of the first version and the possible later extensions was published in March 1971 [13]. In this section, I will give a summary of the project specification and explain the key estimates. In Section 5.4, I will compare it to the actual progress of the project.

The project specification was 25 closely written pages. The facilities were described as follows. For each type of peripheral device there was described the strategy to be used by Boss for handling it and the actions to be taken by the operator. The devices considered were: typewriter-like terminals, paper tape reader, printers, several types of magnetic tape stations, several kinds of drums and disks.

The on-line commands, the implementation, and conventions for the on-line editor were outlined. Also described were the resource allocation on backing stores, the job scheduling and swapping strategies, the user catalog, the account and statistics files.

One section estimated the storage demands and the total system overhead.

A ten-page section described 21 major extensions of the basic project to be decided before implementation started. They included things like conversational jobs (the basic version proposed only remote job entry combined with fast on-line editing), vdu-terminals, card reader, remote batch terminals, and simple facilities for process control experiments.

These parts of the report were published. The unpublished part (five pages) defined the extent of the project, the preconditions, the time schedule, the use of man-months and computer time, the cost for extensions of the basic project, and the necessary implementation group.

The extent of the project fixed the relations to other parts of the software, accounting programs, writing of manuals, transitions to maintenance, and—of course—the facilities as described above. Some facilities which were not considered, but which might be important, were pointed out.

The preconditions stated that certain other software parts should be finished at certain times, that 76 hours of computer time should be available for debugging, that the extensions had to be decided and the specification accepted within a month.

A total of four persons (the three designers and Bjørn Ørding-Thomsen) were assumed as the implementation group with a time schedule built on check points as follows:

November 1970. Final decisions on extensions.
December 1970. Detailed specification of the internal structure and the interface between all parallel activities inside Boss.
February 1971. Debugged Central Logic. All other parts punched.
May 1971. Prototype debugged.
July 1971. Installation of the prototype completed.

In view of the later facts that the prototype was completed April 1972, and the first public release was August 1972, this time schedule seems utterly ridiculous. Let us see, however, how we arrived at it.

The key point was the estimate of the total number of instructions. Our basis was the list of facilities and strategies—not horrible—which we estimated as equivalent to our Algol compiler:

First estimate: Boss is 7,000 instructions.

From this the rest was deduced. An old rule of thumb told that in a project from design to maintenance, a programmer produced an average of 200 machine instructions a month. Thus *35 man-months* were necessary. Of these 6 were spent already with design (3 persons in 2 months), so 29 were left for 4 persons. This brought us to June 1971. We specified July to be cautious.

Another rule of thumb told that a good programmer made one error or design fault for each 20 instructions and that he could find one error for each test run. With the debug technique we were accustomed to, a good test run with succeeding careful inspection of the test output could reveal about 5 errors. To be careful because of the multiprogramming, we assumed that only half an error could be found and corrected for each test run.

So the 7,000 instructions should give 350 errors and 700 test runs. The modular design of the system was estimated to be sufficiently good so that the four programmers could work nearly independently of each other, reducing the debug demand to 200 sessions at the computer. We planned the debug sessions to 15 minutes each, i.e. a total of 50 hours, and asked for 76. The main debug period should be February, March, April (80 days), so two periods of 15 minutes a day should be sufficient.

In order to utilize periods of 15 minutes, we planned the debug sessions carefully, as explained in the next section.

5.2 Planning a Debug Session

A new and extended version of the Monitor was to be used together with Boss, so that a total exchange of the software had to take place during each debug session. We devised a method for a fast exchange of the system based on exchange of disk packs and swap of drum contents to the disk.

A special autoload paper tape was used to switch at the beginning of each session, and another tape was used to switch back to the end of the session. This took a total of 5 minutes.

When we had used this system for a few weeks, we happened to load the start tape at the end of the session—and the entire standard system disappeared and had to be loaded from magnetic tape. The computer staff responded by only allowing us run time in the night after saving the standard system on tape. We responded by changing the autoload tapes to one which itself found out which of the two actions to perform. After a while we regained our short periods of day time.

After reduction for the switch time, we were left with 10 minutes of which we wanted to use four times 1 minute for the planned translation and test of the four programmer's parts. The 6 minutes left were spares for rush corrections. In order to translate and generate a new version in half a minute, all files had to be on disk and only a small text file had to be translated into binary form. No linker (loader) exists in RC 4000, so we had to implement a special linker which loads the binary files into the virtual store in which Boss runs. A simulation program was also devised to feed Boss with input lines from "terminals", etc., in the 30 seconds left.

We used the well-proven technique of permanent test output [17] from all parts of Boss, so that the result of a test run was a list of test output for later inspection of what had happened. This test output is still used in the normal production run, where it is stored on disk or magnetic tape for analysis if the system breaks down [14, Chap. 9, Installation and Maintenance]. A test output record is generated by the Central Logic whenever a coroutine executes *sig*, *wait*, etc. Some coroutines also produce private test output records showing intermediate results.

Obviously, listing of source programs were the exception rather than the rule. With a careful marking of all corrections in the latest listing, we had no troubles finding our way in the latest version. An important point was the use of an extremely careful programmer—Isabella Carstensen—for the clerical work of keeping track of paper tape corrections, keeping track of on-line rush corrections, punching correction tapes according to pencil marks in the listings, arranging safety copies, etc. This work was drastically underestimated in the planning stage.

Finally, the system of project file directories and private file directories (planned for the extended monitor) was utilized in the debug sessions to assure that one test file could be tested together with reasonably good versions of the other files [14, Section 4.6.3, User's Manual]. The decision that a private file was reasonably good and could be made a project file had to be taken between debug sessions after careful inspection of the test output.

5.3 Choice of Programming Language, Paging

The author had previously been involved in the development of Boss 1 in Algol 5 for RC 4000. Although Algol 5 was sufficient for the purpose, the necessary use of reentrant coroutines was very cumbersome to express in Algol. Worse, however, was that the object code turned out to be 4 to 5 times longer than equivalent handwritten assembly language code. With the same overhead in page transfers this would need 4 to 5 times more core store.

It should be noted that the Algol 5 compiler generates fairly good code. For instance it is claimed that Algol W on IBM 360 generates very efficient code, but investigations have shown [1] that it is just as long as Algol 5 code.

As the long object code was prohibitive for the goals of Boss 2, assembly language was chosen.

From the beginning it was assumed that the code and variables of Boss were to be in a virtual store controlled by a software paging system. RC 4000 has no hardware for paging, so software page references must be inserted where needed. We had experience with this kind of software paging from several Algol compilers. The main problem was the hand-written standard procedures which had to fit into a few of the fixed size pages. Whenever changes were needed, it caused great troubles to fit the new version into the fixed size pages. Another problem was a lot of difficult *paging bugs* caused by code which had brought a page to core and later referenced it with an absolute address when it was possibly not in core any more.

We solved the first problem by designing the paging system for variable length pages. We partially solved the second problem (paging bugs) by allowing a coroutine to specify that an entire set of pages had to reside in core simultaneously when it was running.

5.4 Actual Time Schedule

The first check point on the time schedule concerned the final decisions on extensions. They were delayed 6 weeks due to disagreements between the user groups. The extensions chosen were vdu-terminals, card reader, job controlled selection of print forms, printer back-up on magnetic tape. According to the project specification, this should delay the installation by three months (of which 6 weeks were due to the delay of the decision).

The next check point was apparently reached on schedule with release of the report "Boss 2, Internal Structure" dated January 1971. However, a close reading of the report reveals many missing details in the interface between the coroutines. The report contained a detailed version of Sections 2, 3, and 4 of this paper.

In March and April 1971 the company changed their development policy, claiming that they would neglect, somehow, the RC 4000 and try to find other areas for the development groups. The Boss 2 group was heavily involved in these discussions and a delay of one month was accepted. The new schedule looked like this:

May 1971. Debugged Central Logic. All other parts punched.
September 1971. Prototype debugged.
November 1971. Installation completed.

The Central Logic was debugged on schedule, but most other parts were still not written. A lot of detailed revisions of the schedule were made, but none of them reflected reality. Several parts were completed and debugged, and around July 1971 about half of the system was in the test phase.

A general reluctance to face the facts caused me—as a project manager—to discard all planning and just let the group implement as fast as possible. Around August 1971, the group was augmented with Bo Jacoby and Bo Tveden Jørgensen, and the responsibilities of the group were extended to also cover some related software projects excluded in the project specification.

In January 1972 everything was in the test phase, but some parts were in a preliminary version. This point most likely corresponded to the check point "All Parts Punched," but the delay was 8 months.

In January 1972 we finally detected the real reason for the delay. We had programmed *20,000 instructions* instead of the estimated 7,000. When the project entered the maintenance stage in August 1972, we had programmed *26,000 instructions* (including a few further extensions).

The prototype was put in operation in April 1972. Further extensions for conversational jobs (time sharing) and process control were implemented until August 1972, when the first public release took place. At that time 115 man-months had been used instead of the latest estimate of 55 man-months.

5.5 Conclusion

The main fault in the estimates was that the number of instructions were underestimated by a factor of 3 (excluding contributions from later extensions). A possible cause for this—pointed out by Peter Naur—is that we initially compared the project to an Algol compiler which used a very advanced table technique to bring down the program length [17]. A similar technique was not used in Boss, possibly because we concentrated too much on the structuring into coroutines and forgot to design the sequential algorithms inside each coroutine in the same careful manner. Another cause may be that each facility and strategy were conceived and implemented individually, whereas an Algol compiler benefits from the extremely homogeneous structure of Algol 60.

A secondary reason for the underestimate was the interface to the Monitor. The Monitor was extended in the same period with several facilities needed by Boss. Especially the interface concerning drum and disks was much more complicated to utilize than anticipated. This problem was felt severely during the development and caused major revisions of Boss and the Monitor.

A minor contribution to the underestimate is the late inclusion of further extensions and related projects (user catalog updating, accounting, process control, etc.).

A main fault in the project management (the author primarily) was the sticking to a time schedule instead of revising the more fundamental estimate of the number of instructions. It is typical that the main influence of the underestimate is in the programming phase. The debug phase and the installation phase were not so significantly affected.

The rule of thumb saying 200 instructions per man-month may now be checked for the actual schedule: 26,000 instructions/115 man-months = 230.

What might have helped us in the planning was a similar rule of thumb for the programming phase alone.

6. Evaluation

6.1 Performance

The facilities as originally specified were implemented, sometimes in an extended version. We dropped one extension—the vdu-terminals—because the hardware was not developed. Another extension—printer back-up on magnetic tape—has not been put in operation, partially because there seems to be no serious need for it.

The backing store and core store requirements are in good agreement with the specification. However, the system overhead was somewhat underestimated. When Boss runs in the specified core area (15,000 characters), the overhead is many times more than estimated because of thrashing. When Boss uses 30,000 characters in the core store, the overhead is 1.5 times the estimate (actually 3 seconds overhead to execute a job). The larger core demand is related to the code being 3 times longer than estimated. The factor 1.5 could easily have been anticipated if a more detailed analysis was carried out in the specification phase.

6.2 Reliability, Bugs, Proof

When we started the Boss 2 design, we knew that the RC 4000 software was extremely reliable. In a university environment, the system typically ran under the simple operating system for three months without crashes. Although some errors existed in compilers and utility programs, they affected, at most, one job. The crashes present were possibly due to transient hardware errors. Errors in the peripherals were more frequent, but did not wreck the rest of the system.

From the beginning, we aimed at a similar stability for Boss six months after release. So we did not implement any restart facilities, except that the permanent files on disk were preserved by a simple strategy. We believe that this decision is a major reason for the relatively simple and stable operating system.

In fact, Boss 2 passed a 3-week delivery test in September 1972—one month after the first release. In these 3 weeks the contract allowed at most four crashes because of hardware or software. Actually four crashes occurred, three of them caused by bugs in Boss. In the period the system was heavily loaded with unrestricted user jobs: program debugging, process control jobs, and conversational jobs.

From September 1972 to March 1973, dozens of errors were reported as the users explored the corners of the system. In April 1973 all reported errors, except one, were located and corrected. Today the system seems to be error free. The corrections nearly always converged in the sense that one correction did not cause errors somewhere else.

We have collected all corrections during the development and maintenance, but we have not done statistical analysis on them. Nearly all errors are simple programming errors that occur also in uni-programming (loading a wrong register, testing a wrong condition). The most difficult bugs to find were associated with paging (paging bugs, see Section 5.3), and the correct return of borrowed resources (see below).

A few bugs were typical multiprogramming bugs: forgetting to reserve a resource which then happened to be used by another coroutine at the same time. One case of Deadlock occurred (see Section 3.2), but it was simple to correct.

The only important design faults were those associated with booking of resources on the backing store and parallel access to files. I am afraid we still have only a superficial knowledge of these problems (see [16]).

The successful detection and correction of errors after release of the system could not have been achieved without the permanent test output (Section 5.2). If the system broke down, the computer staff would send the test output file to the project group, which then was able to find the error in most cases. As normally only a short backing store file (80,000 characters) is used for cyclical collection of test output, some errors were still difficult to find because they occurred a long time before the symptoms. For instance, if a resource is borrowed and later only a part of it is returned, it will take a long time before something wrong becomes apparent. The cause is then not available in the test output. In the cases where we have had test output on magnetic tape (one large reel every three hours), we have always been able to locate the error—possibly by means of an ad hoc program for analyzing the tapes.

The prototype was very carelessly tested, but after it had been put in operation nobody had time to make careful, systematic test programs. I believe that if the prototype had been delayed some months, we could have found most errors via systematic test programs.

The question of proving an operating system is sometimes discussed. We have proved some statements about the system, for instance the absence of Deadlock. However, in order to prove the entire system, we would have to formalize every statement in the manuals (120 pages) and prove them. Still I doubt whether a statement like "absence of Deadlock" would have emerged from the manuals. It seems to me that the only systems which can realistically be proved are those where the entire manual is below, say, 10 pages.

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I would like to thank Peter Lindblad Andersen and Hans Rischel for their patient development and modifications of the Monitor and the utility programs.

An independent project run by Ole Caprani, Lise Lauesen, and Flemming Sejergård Olsen extended the system to serve also as a remote batch terminal for CDC 6400 and Univac 1106.

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Appendix A. Survey of Coroutines in Boss

The list below refers to Figure 3 and mentions all coroutines in a row by row sequence.

Request Display. Prints messages to the operator on the main console. Messages demanding action from the operator are kept until the action is completed (Section 3.2).

Commandio. One commandio to each on-line terminal and to the operator's console. Performs all conversation with the on-line user and the operator, including editing and listing of files. Some commands are passed on to other coroutines (commands like "run job," "kill job," "start printer").

Termout. One termout to each on-line terminal.

Prints job output on the terminal from a multi-buffer on disk. For nonconversational jobs the progress of the job is not delayed by the slow terminal.

Ps-printer. One ps-printer to each physical printer. Prints completed files from the backing stores or job controlled output from a multi-buffer. Attempts to minimize change of paper type (see Section 2.3). Communicates with request display about change of paper, etc.

Tape Printer. May copy print files from the backing store to a magnetic tape. When the backing store is about to run full of print files, the tape printer asks the operator for a tape and copies the files.

Ps-job. One ps-job to each on-line terminal plus spares for execution of batch jobs and internally generated jobs. A ps-job interprets the job specification (the first job control command), loads possible data files from card or paper tape, reserves most of the temporary resources for the job, and creates and starts the job process.

Now the ps-job receives messages from the job process (all parent messages and some input/output messages). Some messages are checked and then passed on to other coroutines (e.g. print a backing store file, write special operator request). In the same queue the ps-job receives certain buffers from commandio ("kill job," "answer to special operator request"), from remoters (tape ready), and from timer (time exceeded). Messages which will cause a longer waiting time cause the ps-job to ask the Banker to swap out the job meanwhile.

When the job is finished, the ps-job cleans temporary files, asks for rewind of tapes, produces account records, etc.

Job. The job process. In a given moment only some of the ps-jobs have associated job processes.

Unknown Sender. Receives messages from unlogged terminals and processes other than Boss jobs. May either pass the login request to a free commandio, or enroll an internal job (via Banker and a free ps-job), or reject the message.

Rewinder. One rewinder to each magnetic tape station. Rewinds the tape when it is released. Unloads the tape when the station is to be used for something else. A short queue of such requests may exist because the unload cannot be ordered until the tape is rewound.

Remoter. One remoter to each magnetic tape station. Reads the tape label when the operator sets the station in the remote state. Tells request display if the label is unreadable or if the tape is not needed now. Obeys operator commands telling the name of the tape or asking for a label to be written.

When the tape has been identified in one way or another, a possible ps-job waiting for the tape is activated.

Watch-dog. Detects whether a station has been set remote and activates the corresponding remoter. This coroutine is only needed because the Monitor has a special driver process responding to any station set in remote.

Ps-reader. Loads paper tapes either via a multi-buffer as "job controlled input" or via a double buffer to a backing store file. Tells the Banker when the reader becomes empty and available for other jobs.

Ps-card. Loads card files just like the ps-reader. Tells the Banker when a job separation card is met (this signals the presence of a new job in the reader).

Kit Changers. One kit changer to each disk drive with exchangeable kits. Clears up on the old disk pack when the operator requests a kit change, waits until the new kit is ready, reads the kit label, and adjusts the file catalog.

Timer. Supervises the run time of the jobs in the core store and tells the ps-jobs when time has expired.

Banker. The Banker receives records and handles them in one out of three rather different parts of the code with different status in the hierarchy of coroutines. Banker 1 receives requests for swap in and swap out of jobs and performs the swapping on a priority basis. Banker 2 receives requests for reservation or relase of temporary resources (Section 3.2). Finally Banker 3 handles the idle ps-jobs and tells them when to start running a job and the kind of the job (card job, paper tape job, internally generated job).

Pager. Handles the virtual store as described in Section 4.1.