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Notes on the "Worm" programs -- some early experience with a distributed computation

by John F. Shoch and Jon A. Hupp

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Abstract: The "Worm" programs were an experiment in the development of distributed computations -- programs that would span machine boundaries, and also replicate themselves in idle machines. A "worm" is composed of multiple "segments" each running on a different machine. The underlying worm maintenance mechanisms were responsible for maintaining the worm -- finding free machines when needed, and replicating the program for each additional segment. The worm control procedures require some careful design, but this mechanism made each worm a very dynamic and robust program.

These techniques were then used to support several real applications, ranging from a simple multi-machine test program to a more sophisticated real-time animation system harnessing multiple machines.

The worm programs have helped to demonstrate that the tools are at hand for experimenting with distributed computations.

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XEROX
PALO ALTO RESEARCH CENTER
3333 Coyote Hill Road / Palo Alto / California 94304

"I guess you all know about tapeworms...? Good. Well, what I turned loose in the net yesterday was the ... father and mother of all tapeworms."...

"My newest -- my masterpiece -- breeds by itself."...

"By now I don't know exactly what there is in the worm. More bits are being added automatically as it works its way to places I never dared guess existed."...

"And -- no, it can't be killed. It's indefinitely self-perpetuating so long as the net exists. Even if one segment of it is inactivated, a counterpart of the missing portion will remain in store at some other station and the worm will automatically subdivide and send a duplicate head to collect the spare groups and restore them to their proper place."

John Brunner, *The Shockwave Rider*, Ballantine, 1975, pp. 249-252.

1. Introduction

In his book *The Shockwave Rider*, John Brunner developed the notion of an omnipotent "tapeworm" program running loose through a network of computers -- an idea which may seem rather disturbing, but which is also quite beyond our current capabilities. Yet the basic model is a very provocative one: a program or a computation that can move from machine to machine, harnessing resources as needed, and replicating itself when necessary.

In a similar vein, we once described a computational model based upon the classic science fiction film, *The Blob*: a program could start out running on one machine, but as its appetite for computing cycles grew it could reach out, find unused machines, and grow to encompass those resources. In the middle of the night such a program could mobilize hundreds of machines in one building; in the morning, as users reclaimed their machines, the "blob" would have to retreat in an orderly manner, gathering up the intermediate results of its computation. Holed up in one or two machines during the day, the program could emerge again later as resources became available, again expanding the computation. (This affinity for night-time exploration lead one listener to describe these as "vampire programs.")

These kinds of programs represent one of the most interesting and challenging forms of what we once called *distributed computing*. Unfortunately, that particular phrase has already been co-opted by those who market fairly ordinary terminal systems; thus, we prefer to characterize these as *programs which span machine boundaries*, or as *distributed computations*.

In recent years we've seen the emergence of a rich computing environment in which one might pursue these ideas: large numbers of powerful computers, connected with a local computer network and a full architecture of internetwork protocols, and supported by a diverse set of specialized network servers. Against this background, we have undertaken the development and operation of several real, multi-machine "worm" programs; this paper is a report on those efforts.

In the sections which follow, we describe the model for the worm programs, how they can be controlled, and how they were implemented. We then briefly describe five specific applications which have been built upon these multi-machine worms.

It's worth noting here that the primary focus of this effort has been on getting some real experience with these programs. The work did not start by specifically addressing formal conceptual models, verifiable control algorithms, nor language features for distributed computation; but the experience provides some interesting insights into these questions, and helps to focus our attention on some fruitful areas for further work.

2. Building a worm

A *worm* is simply a computation which lives on one or more machines. The programs on individual computers are described as the *segments* of a worm; in the simplest model each segment carries a number indicating how many total machines should be part of the overall worm. The segments in a worm remain in communication with each other; should one of those segments fail, the remaining pieces have the task of finding another free machine, initializing it, and adding it to the worm. As segments (machines) join and then leave the computation, the worm itself seems to move through the network. [In computing we frequently refer to both machines and programs in anthropomorphic terms. In working with "worms" there has been a natural tendency to employ biological terms (albeit rather loosely); thus, a newly-created segment is sometimes referred to as a *clone*.]

It's important to understand that the worm mechanism is used to gather and maintain the segments of the worm, while actual user programs are then built on top of this mechanism.

Initial construction of the worm programs was simplified by the use of a rich but fairly homogeneous computing environment at the Xerox Palo Alto Research Center. This includes over 100 Alto computers [Thacker, *et al.*, 1979], each connected to an Ethernet local network [Metcalfe & Boggs, 1976; Shoch, in press]. In addition, there is a diverse set of specialized network servers, including file systems, printers, boot-servers, name-lookup servers, and other utilities. The whole system is glued together with the Pup architecture of internetwork protocols [Boggs, *et al.*, 1980].

Many of the machines remain idle for lengthy periods, especially at night, when they regularly run a memory diagnostic. Instead of viewing this as 100 independent machines connected to a network, though, it can be viewed as a 100-element multi-processor, in search of a program to run. There is a fairly straightforward set of steps involved in building and running a worm on this set of resources.

2.1. General issues in constructing a worm program

Almost any program can be modified to incorporate the worm mechanisms; all of the examples described below were written in BCPL for the Alto. There is, however, one very

important condition: since the worm may arrive through the Ethernet on to a host with no disk mounted in the drive, the program better not try to access the disk! More importantly, a user may have left a disk spinning in an otherwise idle machine; writing on such a disk would be viewed as a profoundly anti-social act.

Running a worm depends upon the cooperation of many different machine users, who must have some confidence in the judgement of anyone who writes a program which may enter their machines. In our work with the Alto we have been able to assure users that there is not even a disk driver included within any of the worm programs; thus, the risk to any spinning disk is no worse then the risk associated with leaving the disk in place while the memory diagnostic runs. We have never identified a case in which a worm program tried to write on a local disk.

It is feasible, of course, for a program to access secondary storage available through the network, on one of the file servers.

2.2. Starting a worm

A worm program is generally organized with several components: some initialization code to run when it starts on the first machine, some initialization when it starts on any subsequent machine, and the main program. The initial program can be started in a machine by any of the standard methods, including loading via the operating system, or booting from a network boot-server.

2.3. Locating other idle machines

The first task of a worm is to fill out its full complement of segments; to do that, it must find some number of idle machines. To aid in this process, a very simple protocol was defined: a special packet format is used to inquire if a host is free. If it is, the idle host merely returns a positive reply. These inquiries could be broadcast to all hosts, or transmitted to specific destinations. Since multiple worms might be competing for the same idle machines we have tried to reduce confusion by using a series of specific probes, addressed to individual machines.

As mentioned above, many of the Altos run a memory diagnostic when otherwise unused; this program gives a positive reply when asked if it is idle.

Various alternative schemes could be used to determine which possible host to probe next when looking for an additional segment. In practice, we've employed a very simple procedure: a segment begins with its own local host number, and simply works its way up through the address space. Figure 1 shows the evidence of this procedure on an Ethernet source-destination traffic matrix (similar to the one in [Shoch & Hupp, in press]). The migrating worm shows up against the other network traffic as the "stair-case" effect. A segment sends packets to successive hosts until finding one that is idle; at that point the program is copied to the new segment, and this host begins probing for the next segment.

2.4. Booting an idle machine

Having located an idle machine, there is still no way in which an Alto can unilaterally be booted through the network. By design, it is not possible to reach in and wrench control away from a running program; instead, the machine must willingly accept a request to restart, either by booting from its local disk or by booting through the network.

After finding an idle machine, a worm segment then asks it to go through the standard network boot procedure. In this case, however, the specified source for the new program is the worm segment itself. Thus, we have this sequence:

1. Existing segment asks if a host is idle. ("Are you willing to become a clone?")
2. The host answers that it is. ("Yes, I'm willing.")
3. The existing segment asks the new host to boot through the network, from the segment. ("Good. Ask to be made into a copy of me.")
4. The newcomer uses the standard Pup procedures for requesting a boot file [Boggs, *et al.*, 1980]. ("Please make me into a clone.")
5. The Easy File Transfer Protocol (EFTP) is used to transfer the worm program to the newcomer. ("Here comes the genetic material.")

In general, the program sent to a new segment is just a copy of the program currently running in the worm; this makes it easy to transfer any dynamic state information into new segments. But the new segment first executes a bit of initialization code, allowing it to re-establish any important machine-dependent state (for example, the number of the host on which it is running).

2.5. Intra-worm communication -- the need for multi-destination addressing

All segments of the worm must stay in communication, in order to know when one of their members has departed. In these experiments, each segment had a full model of its parent worm -- a list of all other segments.

This is a classic situation in which one host wants to send some information to a specified collection of hosts -- what is known as *multi-destination addressing*, or *multicasting* (also called *group addressing*) [Dalal, 1977; Shoch, 1978]. Unfortunately, the experimental Ethernet design does not directly support any explicit form of multicasting. There are, however, several alternatives available [Shoch, in press].

One could use a *pseudo-multicast ID*, where an unused *physical* host number can be set aside as a special *logical* group address, and all participants in the group set their host ID to this value. This is a workable approach (used in some existing programs), but does require advance coordination. In addition, it would consume one host ID for each worm.

Instead, one could use a *brute force multicast*, where a copy of the information is sent to each of the other members of the group. This is one of the techniques which was used with the worms: each segment periodically sends its status to all other segments. This approach does require sending n*(n-1) packets for each update; other techniques reduce the total number of packets which must

be sent. Many of the worms, however, were actually quite small, needing only 3 or 4 machines -- to ensure that they would not die when one machine was lost. In these cases, the explicit multicast was very satisfactory. When an application needs a large number of machines, they can be obtained with one large worm, or with a set of cooperating smaller worms. For example, a program needing 21 hosts can be configured as one 21 segment worm, or as seven 3 segment worms. Using the brute force multicast, the one large worm requires 420 packets for a complete update (21*20), while the second collection of worms requires only 42 packets for an update (7*(3*2)).

This state information being exchanged is used by each segment to independently run an algorithm similar to the one used in updating routing tables in store-and-forward packet switched networks and internetworks: if a host is not heard from after some period of time it is presumed dead, and eliminated from the table. The remaining segments then cooperate to identify one of their number as the parent of the next clone, and the process continues.

2.6. Releasing a machine

When a segment of a worm is done with a machine it needs to return it to the idle state. This is very straightforward: the segment invokes the standard network boot procedure to re-load the memory diagnostic program, that test is resumed, and the machine is again available as an idle machine for later re-use.

This approach does have some unfortunate behavior should a machine crash, either while running the segment or while trying to re-boot. With no program running, the machine cannot access the network and, as we saw, there is no way to reach in from the net to make it restart. The result is to leave the machine stopped, inaccessible to the worm. The machine is still available, of course, to the first user who walks up to it.

3. One of the key problems: controlling a worm

"No, Mr. Sullivan, we can't stop it! There's never been a worm with that tough a head or that long a tail! It's building itself, don't you understand? Already it's passed a billion bits and it's still growing. It's the exact inverse of a phage -- whatever it takes in, it adds to itself instead of wiping ... Yes, sir! I'm quite aware that a worm of that type is theoretically impossible! But the fact stands, he's done it, and now it's so goddamn comprehensive that it can't be killed. Not short of demolishing the net!"

John Brunner, *The Shockwave Rider*, Ballantine, 1975, p. 247.

The previous section provided only a brief mention of the hardest problem associated with worm management: controlling its growth, and maintaining stable behavior.

Early on in these experiments, we encountered a rather puzzling situation. A small worm was left running one night, just exercising the worm control mechanism, and using a small number of machines. When we returned the next morning, we found dozens of machines dead, apparently

crashed. If one re-started the regular memory diagnostic it would run very briefly, then get seized by the worm. The worm would quickly load its program into this new segment; the program would start to run and promptly crash, leaving the worm incomplete -- and still hungrily looking for new segments.

We speculate that a copy of the program became corrupted at some point in its migration, so that the initialization code would not run properly; this made it impossible for the worm to spawn a healthy clone. (This event took place a few days after the Three Mile Island accident -- but we doubt that radiation could induce genetic damage in this kind of work.) In any case, some number of worm segments were hidden away, desperately trying to replicate; every machine they touched, however, would crash. But the building is quite large, and there was no hint as to which machines were still running; to complicate matters, some machines available for worm running were physically located in rooms which happened to be locked that morning -- so we had no way to abort them.

At this point, one begins to get visions derived from Brunner's novel -- running around the building, fruitlessly trying to chase the worm and stop it before it moves somewhere else.

Fortunately, the situation was not really that grim. Based upon an ill-formed but very real concern about such an occurrence, we had included an emergency escape within the worm mechanism. Using an independent control program, we were able to inject a very special antibody-packet into the network, whose sole job was to tell every running worm to stop -- no matter what else it was doing. This inoculation proved successful, and all worm behavior ceased. Unfortunately, the embarassing results were left for all to see: 100 dead machines scattered around the building.

This anecdote highlights the need to pay particular attention to the control algorithm used to maintain the worm. In general, this distributed algorithm is processing incoming segment status reports, and trying to take actions based upon them. On the one hand, you may have a "high strung worm": at the least disturbance or with one lost packet it may declare a segment gone and seek a new one. If the old segment is still there, it must later be expunged.

Alternatively, some control procedures were too slow to respond to changes, and were constantly at less than full strength. Some worms just withered and died, unable to take prompt action to rebuild their resources.

Even worse, however, were the unstable worms, which suddenly would seem to grow out of control -- like the one described above. This mechanism is not yet fully understood, but we have identified some circumstances that can make a worm improperly grow. One factor is a classic failure mode in computer communications systems: the *half-up link* (or one-way path), where host *A* can communicate with host *B*, but not the other way around. When exchanging information about the state of the worm, this may leave two segments with inconsistent information. One host may think everything is fine, while another one insists that a new segment is necessary, and goes off to find it.

Should a network get partitioned for some time, a worm may also start to grow. Consider a two-segment worm, with the two segments running on hosts at opposite ends of an Ethernet cable,

which has a repeater in the middle. If someone temporarily disconnects the repeater, each segment will assume that the other has died, and will seek a new partner. Thus, one two-part worm suddenly becomes two two-part worms. When the repeater is turned back on, the whole system suddenly has too many hosts committed to worm programs

Similarly, a worm which spans different networks may become partitioned if the intermediate gateway goes down for a while, and then comes back up.

In general, stability of the worm control algorithms was improved by exchanging more information, and by using further checks and error detection as the programs evaluated the information they were receiving. For example, if a segment found that it continually had a lot of trouble receiving status reports from other segments, it would conclude that *it* was the cause of the trouble, and it would self-destruct.

Furthermore, a special program was developed to serve as a "worm watcher" monitoring the local network. If a worm were to suddenly start growing beyond certain limits, the worm watcher could automatically take steps to limit the size of the worm, or shut it down altogether. In addition, the worm watcher maintained a running log recording changes in the state of individual segments. This information was invaluable in later analyzing what might have gone wrong with a worm, when, and why.

It should be evident from these comments that the development of distributed worm control algorithms with low delay and stable behavior is a challenging area. These efforts to understand the control procedures paid off, however: after the initial test period the worms ran flawlessly, until they were deliberately stopped. Some ran for weeks, and one was allowed to run for over a month.

4. Applications using the worms

Until now, we have described the procedures used for starting and maintaining worms. In this section, we look at some of the real worm programs and applications which have been built.

4.1. The Existential worm

The simplest worm to build is one which just runs a null program -- it's sole purpose in life is to stay alive, even in the face of lost machines. There is no substantive application program being run; as a slight embellishment, though, a worm segment might display a message on the machine where it was currently running -- "I'm a worm, kill me if you can!"

This was the first worm constructed, however, and was used extensively as the test vehicle for the underlying control mechanisms. After the first segment was started, it would reach out, find additional free machines, copy itself into them, and then just rest. Users were always free to reclaim their machines by booting them; when that happened, the customary worm procedure would find and incorporate a new segment.

As a rule, though, this would only force the worm to change machines at very infrequent intervals. Thus, the program was equipped with an independent self-destruct timer: after a segment ran for some random interval on one machine, it would just allow itself to expire, returning the machine to the idle state. This dramatically increased the segment death rate, and therefore exercised the worm recovery and replication procedures.

4.2. The Billboard worm (or the town crier)

With the fundamental worm mechanism well in hand, we tried to enhance its impact. As we saw, the Existential worm could display a small message for people to see; the "Billboard worm" pushed this idea one step further: a worm could be used to distribute a full-size graphics image to many different machines.

Several of the available graphics programs made use of a standard representation for an image -- pictures either produced from a program, or read in with a scanner. These images could then be stored on a network file server, and read back through the network for display on a user's machine.

Thus, the initial worm program was modified so that -- when first started -- it could be asked to obtain an image from one of the file servers. From then on, the worm would spread this image, displaying it on screens throughout the building. Two versions of the worm used different methods to obtain the image in each new segment: the full image could be included in the program as it moved, or the segment could be instructed to read it directly from one of the network servers.

With the use of a mechanical scanner to capture an image, the Billboard worm was then used to distribute the "cartoon of the day" -- greeting people on their Altos as they came in.

4.3. The Alarm clock worm

The two examples described above required no application-specific communication among the segments of a worm; with more confidence in the system, we wanted to test this capability, particularly with an application that required high reliability. As a motivating example, we chose the development of a computer-based alarm clock which was *not* tied to a particular machine. This would be a program that would accept simple requests through the network, and signal a user at some subsequent time; it was important that the service not make a mistake if a single machine should fail.

The alarm clock was built on top of a multi-machine worm. A separate user program was written to make contact with a segment of the worm, and set the time for a subsequent wake-up. The signalling mechanism from the worm-based alarm clock was a bit convoluted, but effective: the worm would reach out through the network to a server normally used for out-going terminal connections, and would then place a call to the user's telephone!

What makes this an interesting application is the need to maintain in each segment of the worm a copy of the data base -- the list of wake-up calls to be placed. The strategy employed was quite simple: each segment was given the current list when it first came up. When a new request came in, one machine took responsibility for accepting the request and then propagating it to the other segments. When placing the call, one machine notified the others that it was about to make the call, then made the call, and finally notified the others that they could delete the entry.

This was, however, primarily a demonstration of a multi-machine application, and was not an attempt to fully explore the double-commit protocols, nor other algorithms to maintain the consistency of duplicate data bases.

Note also that this is the first application in which it is important for a separate user program to have the ability to *find* the worm, in order to schedule a wake-up. In the absence of an effective group-addressing technique, we used two methods: the user program could solicit a response by broadcasting to a well-known socket on all possible machines, or it could monitor all traffic looking for an appropriate status report from a worm segment.

4.4. Multi-machine animation using a worm

So far, the examples described have made use of a distributed worm, with no central control. One alternative way to use a worm, however, is as a robust set of machines supporting a particular application -- an application that may itself be tied to a designated machine.

An example which we have explored is the development of a multi-machine system for real time animation. In this case, there is a single *control node* or *master* which is controlling the computation, and playing back the animation; the multiple machines in the worm are used in parallel to produce successive frames in the sequence, returning them to the control node for display.

The master node initially uses the worm mechanisms to acquire a set of machines. The master would first determine how many machines are desired, and could then recruit them with one large worm. As discussed above, though, a single large worm may be slow to get started as it sequentially looks for idle machines, and it may be unwieldly to maintain. Instead of using one large worm to support the animation, the master spawns one worm with instructions on how many other worms to gather. This starting worm launches some number of secondary worms, which in turn acquire their full complement of segments (typically, three segments per worm). Thus, one can very rapidly collect a set of machines responding to the master; this collection of machines is still maintained by the individual worm procedures.

Each worm segment then becomes a "graphics machine" with a pointer back to the master, and each reports in with an "I'm alive" message after it is created; the master itself is not part of any worm. The master maintains the basic model of the three-dimensional image, and controls the steps in the animation. To actually produce each frame, though, it need only send the coordinates for each object; the "worker" machine then performs the hidden-line elimination and half-tone

shading, computing the finished frame. With this approach, all of the worm segments can be working in parallel, performing the computationally intensive tasks. The master hands out descriptions of the image to the segments, and later calls upon them to return their result for display as the next image.

The underlying worm mechanism is used to maintain the collection of graphics workers; if one of the machines disappears, the worm will find a new one, and update the list held by the control program. The worm machines run a fairly simple program, that has no specific knowledge about the animation itself. The system was tested with several examples, including a walk through a cave, and a collection of bouncing and rotating cubes.

4.5. A diagnostic worm for the Ethernet

This combination of a central control machine and a multi-part worm is also a useful way to run distributed diagnostics on many machines. We knew, for example, that Alto Ethernet interfaces showed some pair-wise variation in the error rates experienced when communicating with certain other machines. To fully test this, however, would require running a test program in all available machines -- a terribly awkward task to start manually.

The worm was the obvious tool. A control program was used to spawn a three-segment worm, which would then find all available machines, and load them with a test program; these machines would then check in with the central controller, and prepare to run the specified measurements. Tests were conducted with as many as 80, 90, or even 120 machines.

In the particular test of pair-wise error rates, each machine would have a list of all other participants which had been loaded by the worm and registered with the control program. Each host would simply try to exchange packets which each other machine thought to be a part of the test. At the end of the test each machine would report its results to the control host -- thus indicating which pairs seemed to have error-prone (or broken) interfaces.

Figure 2 shows the Ethernet source-destination traffic matrix produced during this kind of worm-based test. To speed the process of gathering all available machines, a three-segment worm would be spawned, and these segments could then work in parallel. Host 217 was the control Alto, and it found the three segments for its worm on hosts between 0 and 20. Those three segments then located and initialized all of the other participants. As described earlier, a simple linear search through the host address space is used by each segment to identify idle machines. To keep the multiple segments from initially pinging the same hosts, however, the starting point for each segment could be selected at intervals in the address space. Each segment does make a complete cycle through the address space, however, looking carefully for any idle machines.

To avoid any unusual effects during the course of the test itself, the worm maintenance mechanism was turned off during this period. If hosts had died, however, the worm could later be re-enabled, in an effort to re-build the collection of hosts for a subsequent test.

At the conclusion of the tests, all of the machines would be released, and allowed to return to their previous idle state -- generally running the memory diagnostic. These machines would boot that diagnostic through the network, from one of the network boot file servers; 120 machines trying to do this at once, however, can cause severe problems. In particular, the boot server becomes a scarce resource that may not be able to handle all of the requests right away, and the error recovery in this very simple network-boot procedure is not fool-proof. Thus, all of the participants in the measurements would coordinate their departure at the end of a test -- each host waits for a quasi-random period before actually attempting to re-boot from the network boot server.

5. Some history: multi-machine programs on the Arpanet

The worm programs, of course, were not the first multi-machine experiments. Indeed, some of the worm facilities were suggested by the mechanisms used within the Arpanet, or demonstrations built on top of the Arpanet:

1. The Arpanet routing algorithm itself is a large, multi-machine distributed computation, as the IMPs continually exchange information among themselves. The computation continues to run, adapting to the loss or arrival of new IMPs. (Indeed, this is probably one of the longest-running distributed computations.)
2. In a separate procedure, the Arpanet IMPs can be individually re-loaded through the network, from a neighboring IMP. Thus, the IMP program migrates through the Arpanet, as needed.
3. One of the earliest multi-machine applications using the Arpanet took place in late 1970, sharing resources at Harvard and MIT to support an aircraft carrier landing simulation. A PDP-10 at Harvard was used to produce the basic simulation program and 3-D graphics data. This material was then shipped to an MIT PDP-10, where the programs could be run using the Evans & Sutherland display processor available at MIT. Final 2-D images produced there were shipped to a PDP-1 at Harvard, for display on a graphics terminal. (All of this was done in the days before the regular Network Control Program was running; one participant has remarked that "it was several years before the NCPs were surmounted and we were again able to conduct a similar network graphics experiment.")
4. "McRoss" was a later multi-machine simulation built on top of the NCP, spanning machine boundaries. This one simulated air traffic control, with each host running one part of the simulated air space. As planes moved in the simulation, they were handed from one host to another.
5. One of the first programs to move by itself through the Arpanet was the "Creeper" built by Bob Thomas of BBN. It was a demonstration program under Tenex that would start to print a file, but then stop, find another Tenex, open a connection, pick

itself up and transfer to the other machine (along with its external state, files, etc.), and then start running on the new machine. So this was a relocatable program, using one machine at a time.

6. The Creeper program led to further work, including a version done by Ray Tomlinson that not only moved through the net, but also replicated itself at times. To complement this enhanced Creeper, the "Reaper" program moved through the net, trying to find copies of Creeper and log them out.
7. The idea of moving processes from Creeper was added to the McRoss simulation to make "relocatable McRoss." Not only were planes transferred among air spaces, but entire air space simulators could be moved from one machine to another. Once on the new machine, the simulator had to re-establish communication with the other parts of the simulation. During the move this part of the simulator would be suspended, but there was no loss of simulator functionality.

This summary is probably not complete nor 100% accurate, but it is an impressive collection of distributed computations, produced within or on top of the Arpanet. Much of this work, however, was done in the early 1970s; one participant recently commented that "It's hard for me to believe that this all happened 7 years ago." Since that time, we have not seen the anticipated blossoming of many distributed applications using the long-haul capabilities of the Arpanet.

6. Conclusions

We have the tools at hand to experiment with distributed computations in their fullest form: dynamically allocating resources and moving from machine to machine. Furthermore, local networks supporting relatively large numbers of hosts now provide a rich environment for this kind of experimentation.

The basic worm programs described here demonstrate the ease with which these mechanisms can be explored; they also highlight many areas for further research.

7. Acknowledgements

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Arpanet-related experiments.

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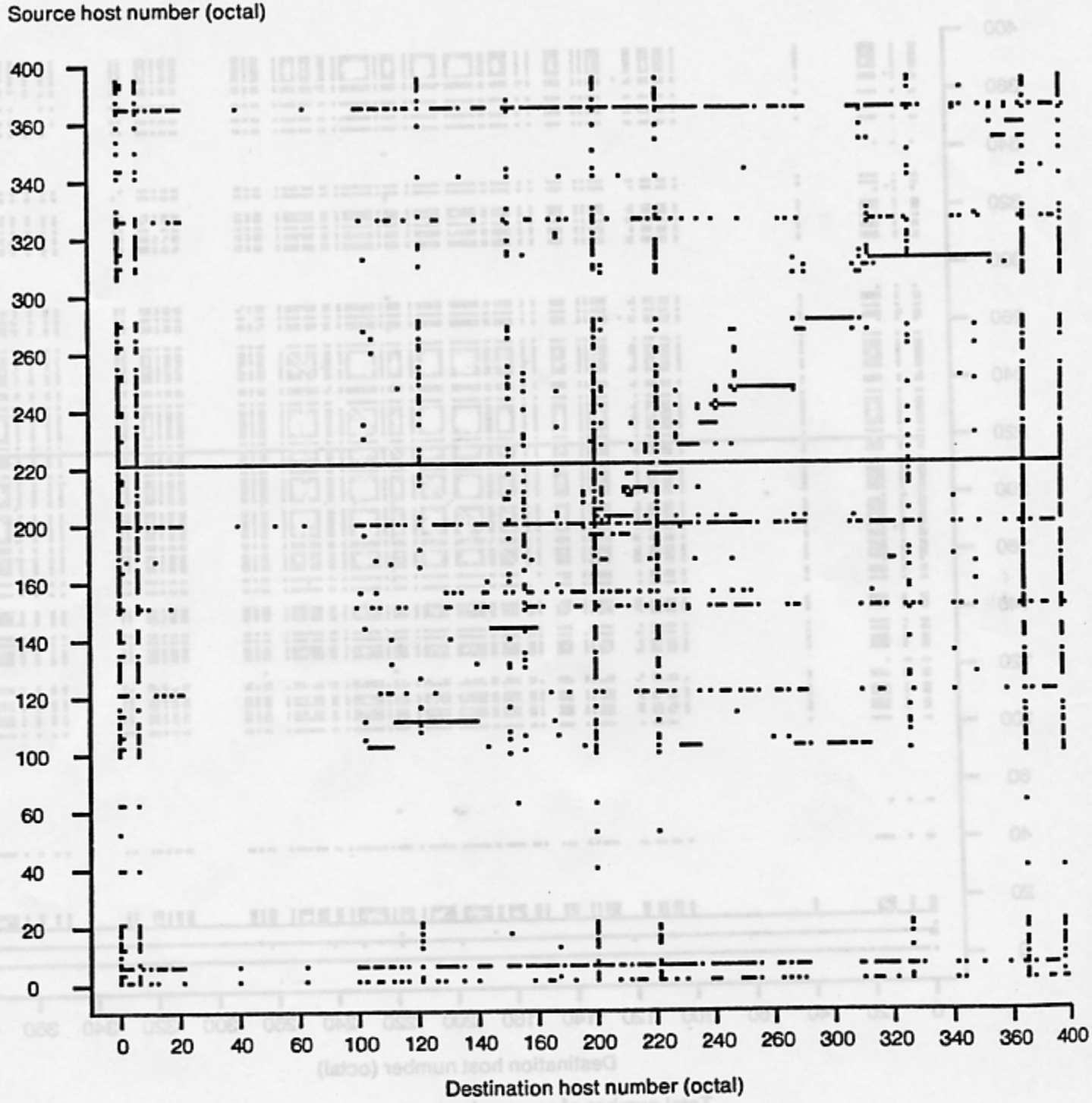
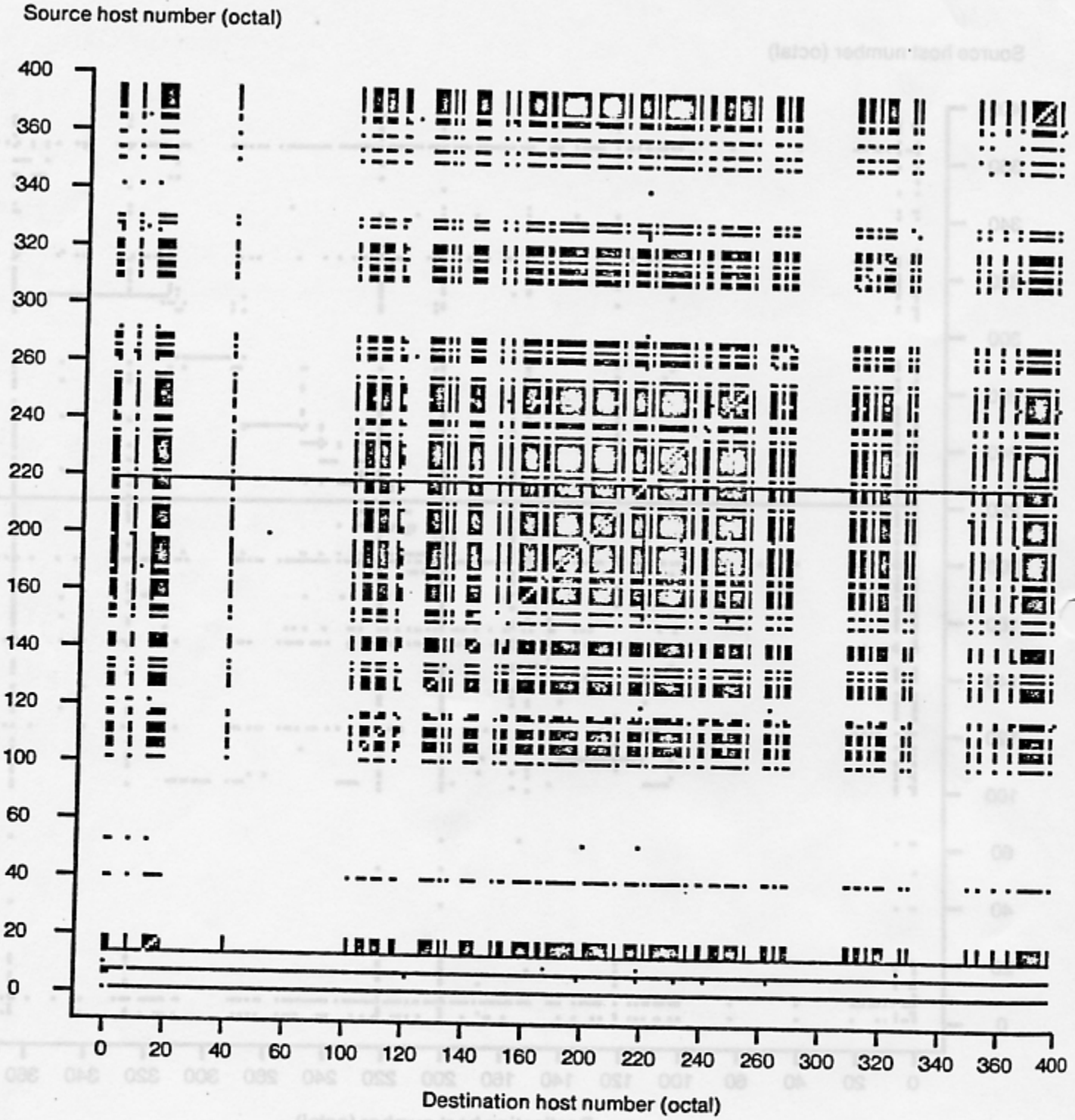


Figure 1: Ethernet source-destination traffic matrix with a "worm" running. (Note the "stair-case" effect as each segment seeks the next one.)



Total number of source-destination pairs = 11,396

Figure 2: Ethernet source-destination traffic matrix when testing Ethernet connectivity.