Vulnerabilities of Network Control Protocols: An Example

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This paper has appeared in the January 1981 edition of the SIGSOFT Software Engineering Notes, and will soon appear in the SIGCOMM Computer Communications Review. It is being circulated as an RFC because it is thought that it may be of interest to a wider audience, particularly to the internet community. It is a case study of a particular kind of problem that can arise in large distributed systems, and of the approach used in the ARPANET to deal with one such problem.

On October 27, 1980, there was an unusual occurrence on the ARPANET. For a period of several hours, the network appeared to be unusable, due to what was later diagnosed as a high priority software process running out of control. Network-wide disturbances are extremely unusual in the ARPANET (none has occurred in several years), and as a result, many people have expressed interest in learning more about the etiology of this particular incident. The purpose of this note is to explain what the symptoms of the problem were, what the underlying causes were, and what lessons can be drawn. As we shall see, the immediate cause of the problem was a rather freakish hardware malfunction (which is not likely to recur) which caused a faulty sequence of network control packets to be generated. This faulty sequence of control packets in turn affected the apportionment of software resources in the IMPs, causing one of the IMP processes to use an excessive amount of resources, to the detriment of other IMP processes. Restoring the network to operational

condition was a relatively straightforward task. There was no damage other than the outage itself, and no residual problems once the network was restored. Nevertheless, it is quite interesting to see the way in which unusual (indeed, unique) circumstances can bring out vulnerabilities in network control protocols, and that shall be the focus of this paper.

The problem began suddenly when we discovered that, with very few exceptions, no IMP was able to communicate reliably with any other IMP. Attempts to go from a TIP to a host on some other IMP only brought forth the "net trouble" error message, indicating that no physical path existed between the pair of IMPs. Connections which already existed were summarily broken. A flood of phone calls to the Network Control Center (NCC) from all around the country indicated that the problem was not localized, but rather seemed to be affecting virtually every IMP.

As a first step towards trying to find out what the state of the network actually was, we dialed up a number of TIPs around the country. What we generally found was that the TIPs were up, but that their lines were down. That is, the TIPs were communicating properly with the user over the dial-up line, but no connections to other IMPs were possible.

We tried manually restarting a number of IMPs which are in our own building (after taking dumps, of course). This procedure initializes all of the IMPs' dynamic data structures, and will

often clear up problems which arise when, as sometimes happens in most complex software systems, the IMPs' software gets into a "funny" state. The IMPs which were restarted worked well until they were connected to the rest of the net, after which they exhibited the same complex of symptoms as the IMPs which had not been restarted.

From the facts so far presented, we were able to draw a number of conclusions. Any problem which affects all IMPs throughout the network is usually a routing problem. Restarting an IMP re-initializes the routing data structures, so the fact that restarting an IMP did not alleviate the problem in that IMP suggested that the problem was due to one or more "bad" routing updates circulating in the network. IMPs which were restarted would just receive the bad updates from those of their neighbors which were not restarted. The fact that IMPs seemed unable to keep their lines up was also a significant clue as to the nature of the problem. Each pair of neighboring IMPs runs a line up/down protocol to determine whether the line connecting them is of sufficient quality to be put into operation. This protocol involves the sending of HELLO and I-HEARD-YOU messages. We have noted in the past that under conditions of extremely heavy CPU utilization, so many buffers can pile up waiting to be served by the bottleneck CPU process, that the IMPs are unable to acquire the buffers needed for receiving the HELLO or I-HEARD-YOU messages. If a condition like this lasts for any length of time,

the IMPs may not be able to run the line up/down protocol, and lines will be declared down by the IMPs' software. On the basis of all these facts, our tentative conclusion was that some malformed update was causing the routing process in the IMPs to use an excessive amount of CPU time, possibly even to be running in an infinite loop. (This would be quite a surprise though, since we tried very hard to protect ourselves against malformed updates when we designed the routing process.) As we shall see, this tentative conclusion, although on the right track, was not quite correct, and the actual situation turned out to be much more complex.

When we examined core dumps from several IMPs, we noted that most, in some cases all, of the IMPs' buffers contained routing updates waiting to be processed. Before describing this situation further, it is necessary to explain some of the details of the routing algorithm's updating scheme. (The following explanation will of course be very brief and incomplete. Readers with a greater level of interest are urged to consult the references.) Every so often, each IMP generates a routing update indicating which other IMPs are its immediate neighbors over operational lines, and the average per-packet delay (in milliseconds) over that line. Every IMP is required to generate such an update at least once per minute, and no IMP is permitted to generate more than a dozen such updates over the course of a minute. Each update has a 6-bit sequence number which is

advanced by 1 (modulo 64) for each successive update generated by a particular IMP. If two updates generated by the same IMP have sequence numbers n and m, update n is considered to be LATER (i.e., more recently generated) than update m if and only if one of the following two conditions hold:

(a) n > m, and n - m <= 32

(b) n < m, and m - n > 32

(where the comparisons and subtractions treat n and m as unsigned 6-bit numbers, with no modulus). When an IMP generates an update, it sends a copy of the update to each neighbor. When an IMP A receives an update u1 which was generated by a different IMP B, it first compares the sequence number of u1 with the sequence number of the last update, u2, that it accepted from B. If this comparison indicates that u2 is LATER than u1, u1 is simply discarded. If, on the other hand, u1 appears to be the LATER update, IMP A will send u1 to all its neighbors (including the one from which it was received). The sequence number of u1 will be retained in A's tables as the LATEST received update from B. Of course, u1 is always accepted if A has seen no previous update from B. Note that this procedure is designed to ensure that an update generated by a particular IMP is received, unchanged, by all other IMPs in the network, IN THE PROPER SEQUENCE. Each routing update is broadcast (or flooded) to all IMPs, not just to immediate neighbors of the IMP which generated

the update (as in some other routing algorithms). The purpose of the sequence numbers is to ensure that all IMPs will agree as to which update from a given IMP is the most recently generated update from that IMP.

For reliability, there is a protocol for retransmitting updates over individual links. Let X and Y be neighboring IMPs, and let A be a third IMP. Suppose X receives an update which was generated by A, and transmits it to Y. Now if in the next 100 ms or so, X does not receive from Y an update which originated at A and whose sequence number is at least as recent as that of the update X sent to Y, X concludes that its transmission of the update did not get through to Y, and that a retransmission is required. (This conclusion is warranted, since an update which is received and adjudged to be the most recent from its originating IMP is sent to all neighbors, including the one from which it was received.) The IMPs do not keep the original update packets buffered pending retransmission. Rather, all the information in the update packet is kept in tables, and the packet is re-created from the tables if necessary for a retransmission.

This transmission protocol ("flooding") distributes the routing updates in a very rapid and reliable manner. Once generated by an IMP, an update will almost always reach all other IMPs in a time period on the order of 100 ms. Since an IMP can generate no more than a dozen updates per minute, and there are

64 possible sequence numbers, sequence number wrap-around is not a problem. There is only one exception to this. Suppose two IMPs A and B are out of communication for a period of time because there is no physical path between them. (This may be due either to a network partition, or to a more mundane occurrence, such as one of the IMPs being down.) When communication is re-established, A and B have no way of knowing how long they have been out of communication, or how many times the other's sequence numbers may have wrapped around. Comparing the sequence number of a newly received update with the sequence number of an update received before the outage may give an incorrect result. To deal with this problem, the following scheme is adopted. Let t0 be the time at which IMP A receives update number n generated by IMP B. Let t1 be t0 plus 1 minute. If by t1, A receives no update generated by B with a LATER sequence number than n, A will accept any update from B as being more recent than n. So if two IMPs are out of communication for a period of time which is long enough for the sequence numbers to have wrapped around, this procedure ensures that proper resynchronization of sequence numbers is effected when communication is re-established.

There is just one more facet of the updating process which needs to be discussed. Because of the way the line up/down protocol works, a line cannot be brought up until 60 seconds after its performance becomes good enough to warrant operational use. (Roughly speaking, this is the time it takes to determine

that the line's performance is good enough.) During this 60-second period, no data is sent over the line, but routing updates are transmitted. Remember that every node is required to generate a routing update at least once per minute. Therefore, this procedure ensures that if two IMPs are out of communication because of the failure of some line, each has the most recent update from the other by the time communication is re-established.

This very short introduction to the routing algorithm's updating protocol should provide enough background to enable the reader to understand the particular problem under discussion; further justification and detail can be found in the references.

Let us return now to the discussion of the network outage. I have already mentioned that the core dumps showed almost all buffers holding routing updates which were waiting to be processed. Close inspection showed that all the updates were from a single IMP, IMP 50. By a strange "coincidence," IMP 50 had been malfunctioning just before the network-wide outage occurred, and was off the net during the period of the outage. Hence it was not generating any updates during the period of the outage. In addition, IMP 29, an immediate neighbor of IMP 50, was also suffering hardware malfunctions (in particular, dropping bits), but was up (though somewhat flakey) while the network was in bad shape. Furthermore, the malfunction in IMP 50 had to do with its ability to communicate properly with the neighboring IMP

29. Although we did not yet understand how it was possible for so many updates from one IMP to be extant simultaneously, we did understand enough to be able to get the network to recover. All that was necessary was to patch the IMPs to disregard any updates from IMP 50, which after all was down anyway. When the network is operating normally, broadcasting a patch to all IMPs can be done in a matter of minutes. With the network operating as it was during the period of the outage, this can take as much as 3 or 4 hours. (Remember that the IMPs are generally unmanned, and that the only way of controlling them from the NCC is via the network itself. This is perfectly satisfactory when an outage affects only a small group of IMPs, but is an obvious problem when the outage has network-wide effects.) This procedure was fully successful in bringing the network back up.

When we looked closely at the dumps, we saw that not only were all the updates on the queue from IMP 50, but they all had one of three sequence numbers (either 8, 40, or 44), and were ordered in the queue as follows: 8, 40, 44, 8, 40, 44, 8, 40, 44, ... Note that by the definition of LATER, 44 is LATER than 40 (44 > 40 and 44 - 40 <= 32), 40 is LATER than 8 (40 > 8 and 40 - 8 <= 32), and 8 is LATER than 44 (8 < 44 and 44 - 8 > 32). Given the presence of three updates from the same IMP with these three sequence numbers, this is what would be expected. Since each update is LATER than one of the others, a cycle is formed which keeps the three updates floating

around the network indefinitely. Thus the IMPs spend most of their CPU time and buffer space in processing these updates. The problem was to figure out how these three updates could possibly have existed at the same time. After all, getting from update 8 to update 40 should require 2 or 3 full minutes, plus 31 intervening sequence numbers. So how could 8 still be around when 40 was generated, especially since no updates with intervening sequence numbers were present?

Our first thought was that maybe the real-time clock in IMP 50 was running one or two orders of magnitude faster than normal, invalidating our assumptions about the maximum number of updates which could be generated in a given time. An alternative hypothesis suggested itself however when we looked at the binary representations of the three sequence numbers:

8 - 001000

40 - 101000

44 - 101100

Note that 44 has only one more bit than 40, which has only one more bit than 8. Furthermore, the three different updates were completely identical, except for their sequence numbers. This suggests that there was really only one update, 44, whose sequence number was twice corrupted by dropped bits. (Of course, it's also possible that the "real" update was 8, and was corrupted by added bits. However, bit-dropping has proven itself

to be a much more common sort of hardware malfunction than bit-adding, although spontaneously dropped bits may sometimes come back on spontaneously.)

Surely, the reader will object, there must be protection against dropped bits. Yes there is protection, but apparently not enough. The update packets themselves are checksummed, so a dropped bit in an update packet is readily detected. Remember though that if an update needs to be retransmitted, it is recreated from tabled information. For maximal reliability, the tables must be checksummed also, and the checksum must be recomputed every time the table is accessed. However, this would require either a large number of CPU cycles (for frequent checksumming of a large area of memory) or a large amount of memory (to store the checksums for a lot of small areas). Since CPU cycles and memory are both potentially scarce resources, this did not seem to us to be a cost-effective way to deal with problems that arise, say, once per year (this is the first such problem encountered in a year and a half of running this routing algorithm). Time and space can be saved by recomputing the checksum at a somewhat slower frequency, but this is less reliable, in that it allows a certain number of dropped bits to "fall between the cracks." It seems likely then that one of the malfunctioning IMPs had to retransmit update 44 at least twice, (recreating it each time from tabled information), retransmitting it at least once with the corrupted sequence number 40, and at

least once with the corrupted sequence number 8. This would cause those three sequence numbers to be extant in the network simultaneously, even though protocol is supposed to ensure that this is impossible.

Actually, the detection of dropped bits is most properly a hardware function. The next generation of IMP hardware (the "C30 IMP") will be able to detect and correct all single-bit errors, and will detect all other bit errors. Uncorrectable bit errors will cause the IMP to go into its "loader/dumper." (An IMP in its loader/dumper is not usable for transferring data, and is officially in the "down" state. However, an IMP in its loader/dumper is easily controllable from the NCC, and can be restarted or reloaded without on-site intervention.) Current hardware does have parity checking (which should detect single dropped bits), but this feature has had to be turned off since (a) there are too many spurious parity "errors," i.e., most of the time when the machines complain of parity errors there don't really seem to be any, and (b) parity errors cause the machines to simply halt, rather than go into their loader/dumpers, which means that on-site intervention is required to restart them.

Pending the introduction of improved hardware, what can be done to prevent problems like this from recurring in the future? It is easy to think of many ways of avoiding this particular problem, especially if one does not consider the problems that may arise from the "fixes." For example, we might be able to

avoid this sort of problem by spending a lot more CPU cycles on checksumming, but this may be too expensive because of the side effects it would introduce. (Also, it is not clear that any memory checksumming strategy can be totally free of "cracks.") A very simple and conservative fix to prevent this particular problem from recurring is to modify clause (a) of the definition of LATER so that the "<=" is replaced by "<" (strictly less than). We will implement this fix, but it cannot be guaranteed that no related problems will ever arise.

What is really needed is not some particular fix to the routing algorithm, but a more general fix. In some sense, the problem we saw was not really a routing problem. The routing code was working correctly, and the routes that were generated were correct and consistent. The real problem is that a freakish hardware malfunction caused a high priority process to run wild, devouring resources needed by other processes, thereby making the network unusable. The fact that the wild process was the routing process is incidental. In designing the routing process, we carefully considered the amount of resource utilization it would require. By strictly controlling and limiting the rate at which updates can be generated, we tried to prevent any situation in which the routing process would make excessive demands on the system. As we have seen though, even our carefully designed mechanisms were unable to protect against every possible sort of hardware failure. We need a better means of detecting that some

high priority process in the IMP, despite all the safeguards we have built in, is still consuming too many resources. Once this is detected, the IMP can be automatically placed in its loader/dumper. In the case under discussion, we would have liked to have all the IMPs go into their loader/dumpers when the problem arose. This would have enabled us to re-initialize and restart all the IMPs much more quickly. (Although restarting individual IMPs did little good, restarting all the IMPs simultaneously would have cleared up the problem instantly, since all routing tables in all IMPs would have been initialized simultaneously.) It took us no more than an hour to figure out how to restore the network; several additional hours were required because it took so long for us to gain control of the misbehaving IMPs and get them back to normal. A built-in software alarm system (assuming, of course, that it was not subject to false alarms) might have enabled us to restore the network more quickly, significantly reducing the duration of the outage. This is not to say that a better alarm and control system could ever be a replacement for careful study and design which attempts to properly distribute the utilization of important resources, but only that it is a necessary adjunct, to handle the cases that will inevitably fall between the cracks of even the most careful design.

REFERENCES

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