DD2497 Final Report - Group 5

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1 Countered vulnerabilities

Microkernels often communicate, in some way, with external services for various reasons. By following the principle of least privilege (where each user, process etc has the least amount of privileges possible) you minimize the attack surface, and make it harder for potential malicious actors. Specifically for network traffic this can be accomplished through the usage of a so-called firewall.

The firewall is employed to ensure that only pre-defined traffic is allowed. This is a defensive mechanism to prevent remote exploits that could otherwise be possible on exposed processes, and prevent malicious processes from communicating with a remote host. Specifically it mitigates the effect of and prevents remote exploitation, where a remote adversary may try to gain access to the OS over the network.

With a firewall that can be configured on a per process basis already in place from previous years in this course, we have extended it to also allow firewall rules to only apply to specific users. By implementing firewall settings per user, this further improves the security of the microkernel as some users can have restricted internet traffic.

Firewalls that are implemented per-user are useful in many situations. For example, a large finance company could have employees who don't have enough knowledge about being safe online. Therefore, there could be root users in the company, in this case IT-technicians, that have more privilege than the other employees. These root users could have access to important websites that not everyone should have.

2 Design choices

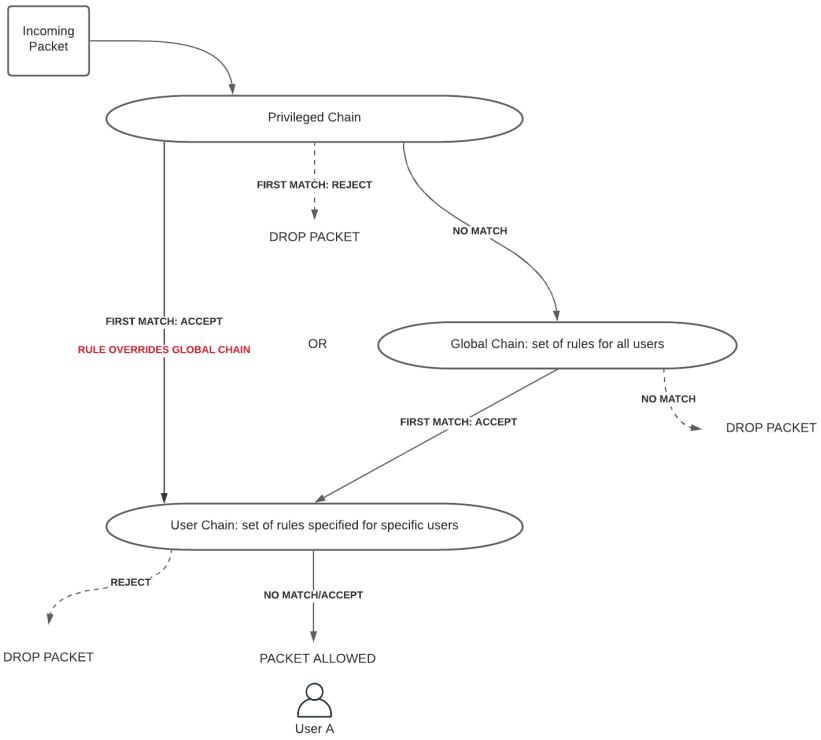
The Linux distribution comes packed with several firewalls, a popular one is *iptables*. *iptables* defines different chains, which are lists of rules to determine if an internet connection should be allowed, rejected or dropped. Polices will attempt to match packages coming in on properties such as IP (destination or source), port, protocol and more. The chains use a first-match approach, which means whichever rule first matches a packet will determine what to do with it. Therefore, the order of rules matter: default, or catch-all, rules are of course placed at the end. The first-match approach has significant performance advantages for complex firewalls that have a lot of rules.

The previous firewall that we built our implementation upon used a different approach, where each rule had an associated priority level. This allowed all new rules to simply be added to the beginning of the rules list, and then prioritizing between multiple matching rules were done through the priority field (with same priority going with a last-match approach). Furthermore, all rules were placed in either the *in_rules* list or the *out_rules* list, based on if the rule regarded incoming or outgoing traffic.

However, this has the drawback of having to check every single rule (of either the "in" or "out" direction) every time, since we can't know if there is a matching rule with a higher priority later in the list. Because of this, we chose to modify the existing firewall to function more like *iptables*, with multiple chains that all utilize a first-match approach.

The general idea is that we have different "levels" of chains, which are considered in order. That is, we first consider the first chain, and when we find a matching rule/have traversed the entire chain without finding a matching rule, we continue to the second chain based on the outcome. In total we have 3 chains.

Figure 1: Design Choices of the chains



The first chain is a set of rules that privileged users can edit to override non-user specific rules. These rules can be either ACCEPT or REJECT policy and when going through the chain, we use the first-match technique, so as soon as there is a matching rule we follow its policy, even if there are other matching rules further down the chain. The main purpose of this chain is to for instance allow admins to set up more lenient rules for themselves.

The second chain is the global chain, which every user is affected by. This chain functions the same way as the previous privileged chain, except that in the global chain all rules apply to all users of the system. The global chain is only considered if we don't find a matching rule in the privileged chain. The intention with this chain is to allow a set of standard rules for a typical user. If no matching rule is found in any of these two chains, we go with a whitelist approach and the packet is dropped.

Essentially, these first two chains function like one entity, with the first matching rule over any of the two being chosen, and if no matching rule is found after traversing both the packet is dropped. The separation into two chains is for clarity and to ensure that if you add a rule meant to override the global chain, it is placed in the privileged chain (which is considered first).

The third, and last chain, is where we have user specific rules for regular users. These rules will only be considered if a packet matched a rule with the ACCEPT policy in one of the previous two chains. This allows non-privileged users to further restrict their traffic if they consider the global rules too lenient. Since only packets allowed by the first two chains reach this chain it cannot be used to increase the lenience of a user's traffic. Because packets that reach this chain are already allowed either on a system level (the global chain) or on a level overriding the system rules (the privileged chain) we consider it safe to use a blacklist approach on this chain, letting through packets that don't match any rule in this third chain. This means that users that are not interested in customizing their own firewall rules can just leave this chain empty without any issues. This is part of the intention with this chain: to allow regular, non-privileged users to block additional traffic if they think the standard, global rules are too lenient. But it shouldn't be required of a regular user to fiddle with this chain (or indeed the firewall at all) if they don't want to.

Since editing the first two chains allows a user to increase network access of any user, they can only be edited by privileged users. Meanwhile, as mentioned in the last paragraph the third chain can't be used to gain more access so it can safely be edited by any user.

The conversion to using chains with a first-match approach and the addition of a user ID to the rules required us to change several signatures of firewall functions and to update the low level implementation of handling firewall rules. For instance, we changed the add and remove functions to utilize an index of where to add/remove a rule. But other than that, we tried to reuse the old implementation and build upon it, rather than replacing it. The firewall is still a server that intercepts network packets and inspects them, and it still has additional checks for incoming TCP packets (we haven't touched this check), and we kept the Command Line Interface (CLI) tool for the firewall (though this required some updates to work with our new structure). This CLI tool allow users to dynamically add, remove and list rules of the firewall without having to restart the entire firewall server.

3 Implementation details

Our first step in adding user ID:s to the firewall rules was to figure out how to gain the correct user ID for a given network packet. In Linux system, processes need to know who is executing a particular process. In Minix, the Process Manager (PM) holds this information. Because users can execute on behalf of other users, and change user, one variable is not enough: three variables are used. The real UID is always the one who is executing, regardless if this is on behalf of some other user. If we are user A and if we execute on behalf of another user B, their user ID will be the effective UID, while the real ID would be our user ID: user A. The saved variable is used internally to handle cases where you need to change user and you do not want to lose information of who it is. It is standard that all programs will verify that the effective UID has correct permissions, and of course our firewall is no different.

Thus, we needed a way to get the effective user ID of a network packet. By looking at the previous firewall implementation we saw that for a given network packet they utilized endpoint information and made a SYSCALL to the PM to retrieve the associated process name. Since the user ID info is also handled by the PM, we added a very similar SYSCALL to the PM that instead retrieved the effective user ID, given endpoint information. This required incrementing the number of SYSCALL:s for the Pm in *minix/include/minix/callnr.h* and *minix/servers/pm/table.c*, adding a new IPC message type in *minix/include/minix/ipc.h*, adding a wrapper function for the SYSCALL in *minix/lib/libsys/getepinfo.c* (and its declaration in *minix/include/minix/syslib.h*), and implementing the SYSCALL in *minix/servers/pm/misc.c* (and declaring it in *minix/servers/pm/proto.h*).

After having access to the user ID we started working on our chains. Like the previous implementation we kept using linked lists stored in the heap for our firewall rules, but we changed the structure. Previously there were two lists: the first consisting of rules for incoming packets and the second consisting of rules for outgoing packets. We saw no need to keep these lists separate, especially knowing that we would already have multiple lists representing our different chains, so we removed this distinction. Then we changed the abstraction a little: the previous implementation was saving the list by knowing the head entry and having every rule contain a pointer to the next and previous rules; making it a doubly linked list. Instead we made a struct representing a chain that wraps a chain ID and a head entry, and we made all entries only have pointers to the following and previous entries, as well as having a pointer to the actual rule. That is, we separated the logical entities of "chain", "entry", and "rule" into different physical entities through different structs, making the separation between them clearer. We also kept the property of the list being doubly linked rather than singly linked, although admittedly we currently do not make use of this.

A rule in the firewall is similar to the previous implementation, but instead of having a priority field (and having pointers to the next and previous rules) it has a user field for the user ID and a direction field (since we no longer have different lists for rules regarding incoming or outgoing packets). In total, this is what a current rule looks like:

```
fw_chain_rule {
  uint8_t type;
  uint8_t action;
  uint8_t direction;
  uid_t user;
  uint32_t ip_start;
  uint32_t ip_end;
  uint16_t port;
  char p_name[MAX_NAME_LEN];
```

```
}
```

, where MAX_NAME_LEN is the longest string allowed for a process name (defined to be 16 bytes by the previous project).

When it comes to operating on rules (adding and removing) our implementation is somewhat different from the previous one. Previously rules were always added at the start of the list, and removing a rule meant looking for the first rule whose fields matched all the arguments to the remove function. We operate on an index basis instead, inserting a rule at the given index, and removing a rule at a given index. This means that removing a rule only takes a chain ID and an index, rather than specifics for all fields. When adding a rule, if the given index is invalid (outside of the list size) then the rule is simply added at the end of the list. For instance one can give the index -1 to always add a rule at the end. If the index is invalid when removing a rule, the list is left untouched and the function only states this in a print and returns.

For matching a rule, the different chains are probed in the order described in the "Design choices" section. For each rule in a chain, it is checked if all fields (except the action field) match the arguments, or if a field of the rule has the "any-value". As the name implies such a field will match any value. If all fields match, then that rule is chosen and its action field determines what happens next (either ACCEPT or REJECT).

The "any-values" are generally defined to be 0 or the null-string (with the exception of user ID since a user can have the ID 0). Thus, when defining enum-like constants (like IN_RULE and OUT_RULE) we tried to avoid using 0 since it might clash with our "any-values". Thus, the enum-like constants we have used start at 1 instead of 0. Speaking of which, we have also tried to define constants for most places where we otherwise would have used "magic constants". This to increase readability and to reduce errors when making changes.

We have generally tried to store all our defined constants of the "fwdec-server" as well as the definition of the chain-related structs in the file $minix/servers/fwdec/fwchain.h$, to keep them in one place. Some of these were also defined in other places relating to the command line utility, or the interface functions other servers would use to contact the "fwdec-server". Because of this, some of the needed constants were removed from the $fwchain.h$ file and were instead imported from the $minix/include/sys/fwctl.h$ header file.

When it comes to the Command Line Interface (CLI) we could keep most of the previous logic, but we still had to update several files since we changed how rules are added and removed, and what fields they contain. In $minix/commands/firewall/firewall.c$ we updated the actual command line command, in $minix/lib/libc/sys/fwctl.c$ (and $minix/include/sys/fwctl.h$) we updated the wrapper functions for making a SYSCALL to the Virtual File System (VFS) (which forwards the IPC-message from the command line utility to the "fwdec-server"), in $minix/include/minix/ipc.h$ we updated the IPC-message carrying info about an issued command line command, in $minix/servers/vfs/misc.c$ we updated how the VFS forwards the IPC-message from the command line utility to the "fwdec-server", and lastly in $minix/servers/fwdec/main.c$ and $minix/servers/fwdec/fwdec.c$ (and in $minix/servers/fwdec/proto.h$) we updated how the "fwdec-server" handled received IPC-messages from the command line utility.

Lastly it is worth mentioning the issues we had with our IPC-message for the CLI. We carefully made sure that all fields would add up to 56 bytes, and yet it mysteriously complained when we did this, and sometimes it compiled when it didn't add up to 56 bytes. In the end we managed to find some consistency indicating that every field of the message-struct had to be contained within one aligned 32 bit word; meaning if our first field was only 1 byte and the second field was 4 bytes, there would be a gap of 3 bytes in our message since the second field would not want to be split over the 3 remaining bytes of the first word and then have its last byte in the next word. Similarly for the entire message, it was allowed to be up to 3 bytes too small, presumably since the next item after it would be aligned to the next free word.

While this is a little difficult to properly explain, and the actual cause is still just a theory on our part, the important takeaway is that the order of the fields in the IPC-message matter. By ensuring that all our fields never ended up "between words" it worked as expected, allowing us to pad the message with the expected amount of padding.

4 How our firewall counters target vulnerabilities

So let's summarize how our firewall implementation achieves its goal. Like the previous implementation, our firewall still intercepts all network packets (both incoming and outgoing) and forwards them to the firewall decision server ("fwdec"). New is that the user ID is also included in the info sent to the decision server. This decision server iterates over all firewall rules contained in the different chains. These different chains allow adding rules that affect different users in different ways: global chain for all users, privileged chain to override this, and user chain to further restrict one's own traffic without needing privilege, as described in section "Design choices". Thus the firewall can both contain rules that affect all users, and rules that only affect specific users. When the decision server finds a matching rule it acts according to the action specified by that rule, or, if no matching rule is found, it acts according to the specification outlined in the "Design choices" section.

To prevent privilege escalation unprivileged users can't modify anything but the rules affecting themselves in the user chain (only privileged users can modify the first two chains); which can only further restrict the access they already have. One important aspect in achieving this is that if no matching rule is found in the first two chains we simply drop the packet without ever going to the user chain, meaning packets that aren't explicitly allowed won't be tested against the chain that unprivileged users can modify.

Thus, our firewall inspects all network packets and can treat them differently depending on what user is executing the process they are associated with. And privileged users can modify the firewall dynamically, while unprivileged users can only modify it in such a way that they further restrict their own access.

5 Future improvements

If the reader is looking at the source code of the project, note that we have inserted TODO:s called "TODO5" (TODO for group 5) to allow us to search for them in the project (there were several previous TODO:s meaning only searching for "TODO" yielded many to us uninteresting results). While we solved the most important ones, some are left as remarks about things we would have liked to do something about but didn't have enough time to. If looking to continue and/or improve our work this is a good place to start.

Otherwise, the main improvement that we thought of but did not have time to implement was the addition of specifying firewall rules for specific groups of users. This would present the issue of having to somehow prioritize firewall rules for the user and for all different groups the user is part of. Should one take the first rule found from either the user or any of the user's groups, or should there be some different prioritization? The group issue could also regard access control of the firewall: could a user be considered unprivileged but be in a privileged group that should be able to edit the firewall?

6 Contribution (André)

In our project we have pair-programmed a lot, meaning we generally were multiple people contributing to the same thing at the same time. Thus, my contribution outlined below will overlap with the contributions of other group members.

Additionally, as the final report was handed in by Tommie, Henrik and Hîvron a week prior to me and Albin. Me and Albin (We) had time to make further additions to the implementation, and partly to the design. These additions are also outlined below, they will not be included above for clarity.

6.1 Initial phase: user-aware firewall

In the first part of the project we mostly worked together as the entire group. We inspected the code of the previous project, discussed what we would keep and what we would change, and how we should implement our extensions. Then we started implementing our version and tried to figure out how to get it to work in Minix.

During this part I, like the rest of the group, partook in the discussions forming our design and wrote code for the implementation of our chains of rules. This involved understanding the previous implementation of adding, removing, listing, and matching rules, and modifying it to fit our needs.

We also added a new SYSCALL to the PM for getting the user ID of an endpoint, by looking at a SYSCALL with similar purpose that the previous group implemented.

This initial phase extended to the demo seminar. All functionality up until then was done as a full group in-person (mostly, in Magenta).

7 Contribution (Albin)

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Additionally, as the final report was handed in by Tommie, Henrik and Hîvron a week prior to me and André. "We" further down in the text will be refered to me and André, thus many part of our contributions will overlap. As our group members handed in their work one week prior to us we had time to make further additions to the implementation, and partly to the design. These additions are also outlined below, they will not be included above for clarity.

7.1 Getting started

In the beginning of the course I created the Git repository, downloaded, configured and pushed everything to GitHub in order to make the start of the project a little bit easier. However, it turned out that we had to redo our repository as I did not know that we needed the git history and same folder- and file structure as the original repository. However, I quickly fixed that as well.

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This initial phase extended to the demo seminar. All functionality up until then was done as a full group in-person (mostly, in Magenta).

7.3 Firewall usage by unprivileged users

We targeted an optional requirement, that any user can modify the user chain. We planned this solution together and noticed we had to make changes in many places in the CLI program and fwdec server. The most time-consuming part was figuring out where to make the changes, as the VFS server was also involved.

7.3.1 CLI

The effective uid must be root to do any operation on the privileged and global chains. But any user can modify the user chains (send syscalls with messages for the user chains). We also set the appropiate default values for different cases depending on who is executing the command and which command is executed. We planned and implemented this together as it was difficult to work on these changes by ourselves.

7.3.2 Adding logic for unprivileged users

As every users rules are saved in the same chain we had to implement logic that made sure that the user trying to list, add and remove rules only could see and add/remove ones own rules. Additionally, we implemented logic to enable user-relative indexing on the user chain. Meaning that indexes works

as expected although all users rules were saved in the same chain. Changing this meant writing logic in the CLI and the fwdec server. To make this work we had to add the effective user ID to the functions for listing, adding and removing rules. All of this we planned and implemented together with pair programming.

7.3.3 Notes on security

Sincec the fwdec server allows IPC communication from all targets (including user processes), any user could create a program and send messages to the fwdec and VFS server. This is due to that we had to remove the constraint that only super users could send messages to the fwdec server. To combat this we fetched the effective user id of the sender in the fwdec server by getting executing process information information from the VFS server. Since both theses servers have root privileges we assumed they are to be trusted. The process information is then used to get the effective user id of the sender.

This enabled non-privileged users ti have access to the user chain as the permission-checking logic is done in firewall.c. The effective used id is what's being used to determine which rules to list, add or remove rules giving that they have permission to access the chain. As mentioned earlier, non-privileged users will only have access to the user chain with relative indexing. This way we prevented unauthorized access to the firewall.

7.4 Combining the different chains

As the previous members had laid the ground work on getting the privileged chain to work we added the logic for the user chain and then implemented the rule traversal across the chains as described above in the design diagram. As we did this we found a bug related to how the packets IP was compared to the rule IP ranges.

7.4.1 IP Comparison

The IP addresses in minix are stored as uint32 with the least significant byte of the IP address as the most significant byte if the unsigned int representation. This rendered the checkin if an IP address was within a given range diffictult. To fix this we wrote a function to flip the convert the uint32 representation to a flipped version that we could correctly compare to the IP ranges given in the rules.

Here we could work independently and André wrote the function flip the minix uint32 ip address to a flipped uint32 representation of the IP address. Based on his work I wrote a function, is_ip_in_range that could check whether of not a given IP is in the range of a start (including) and ending (including) IP address.

Our work was then integrated into the matching rule algorithm, thus solving the bug mentioned earlier.

7.5 Refactoring

As aw implemented our changes in the CLI we decided to make it more readable and this refactored almost the entire program. Mainly we separated the parsing of the arguments. To make things further readable we added aliases for the different user chains as well. This made the code and the usage of the CLI easier. In addition to this we gathered the defines into a single file. Previously, the code had a lot of defines that was doing the same thing but on different locations. Making changing the code difficult and prone to bugs as the programmer has to change defines in multiple places.

7.6 Additional TODOs

The rules can be changed dynamically but there is no persistence saving of the rules in place. The only way to have persistence across reboots is by implementing a startup script that adds the necessary rules, like .bashrc works for users-settings in Linux.

Furthermore, as we worked on our part of the implementation we discovered that a couple of additional checks could be a good idea to implement. Currently we do not check from where the messages is being sent. For example, one could add checks to the m.m_source property to ensure that changes and listing of firewall rules originate from the VFS.