Using Packetdrill: a Power Tool for Automated Testing of the Linux Networking Stack

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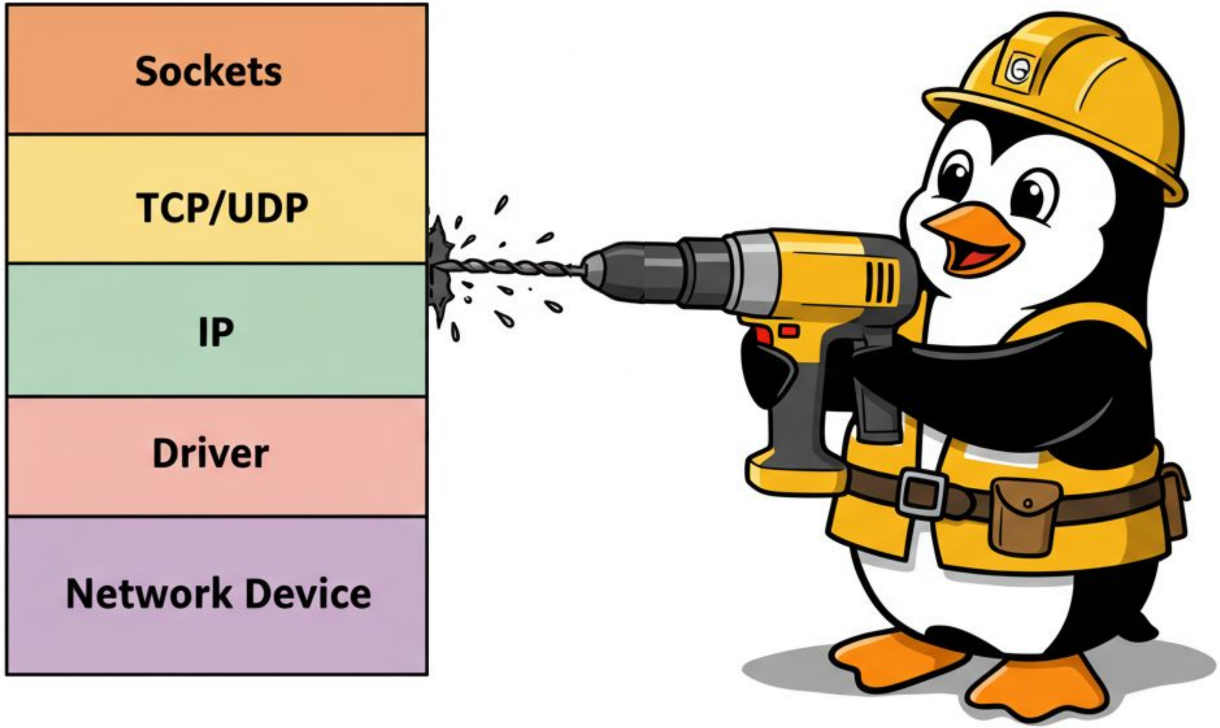

ACKs

The packetdrill tool and the Linux packetdrill test suite are joint open source work by many members of various Networking software teams at Google:

Neal Cardwell, Eric Dumazet, Yuchung Cheng,
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and *Tom Herbert,* ...   [ex-Googlers in italics]

... and many other generous members of the Linux,

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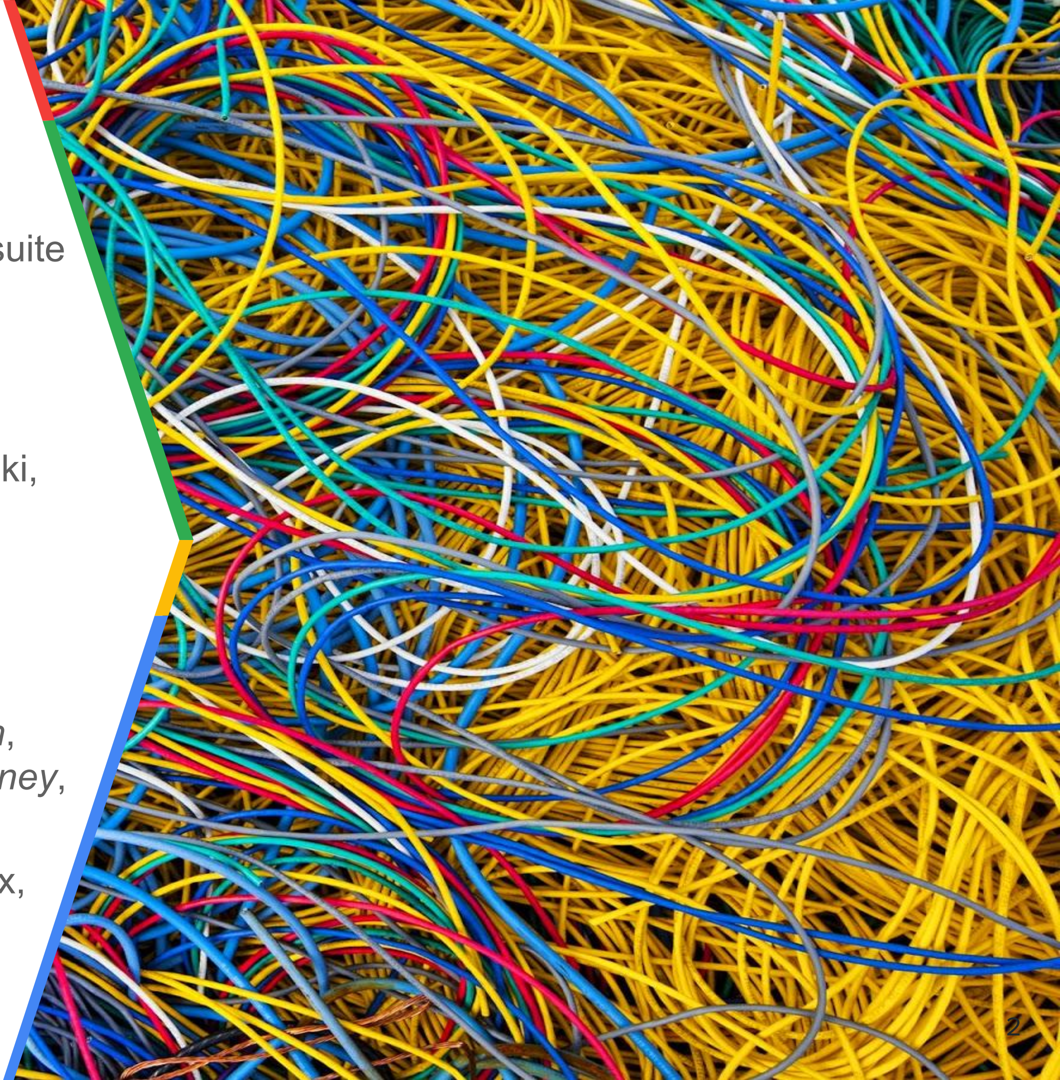
Thank you!



Outline

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  - Goals
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- Using packetdrill: basics
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Part 1: Introduction to packetdrill

What is packetdrill?

- Packetdrill is a scripting tool for unit-testing network stacks
- For entire TCP/UDP/IPv4/IPv6 network stacks
    - From the system call layer down to the NIC hardware
- Works on Linux, FreeBSD, OpenBSD, and NetBSD; ports exist for MacOS
- Has two execution models for testing network stack behavior:
    - **Local**: Within a single machine using a tun virtual network device (for speed and ease)
    - **Remote**: Over a physical NIC on a physical LAN (for testing real drivers and NICs)
- Enables quick, precise (packet-header-level), reproducible, automated tests
- Open source since 2013
    - License: GPLv2, same as Linux kernel
- Interpreted, for fast edit/test cycles
    - Even on production machines w/o build tools

When is packetdrill useful?

- In what phases of software development is it useful?
  - Testing new changes, fixes, or features during development
    - Using black box unit tests
  - Automated regression testing
    - More precise and reproducible than netperf, load tests, or production testing
  - Troubleshooting
    - To replay traces, reproduce issues, test what-if theories
- What aspects of network stacks can it test?
  - Correctness - does the protocol implement the spec?
  - Reliability - does the state machine handle challenging corner cases well?
  - Interoperability - does it handle the kind of packets other stacks send?
  - Performance - are congestion control, loss recovery algorithms correct? (in tricky cases?)
  - Security - how does handle malicious messages?

When not to use packetdrill...

- What kinds of network testing is packetdrill **not** suited for?
  - High-speed or long-duration performance testing (e.g., CPU usage, throughput, latency)
    - Instead, use neper or netperf or iperf/iperf2/iperf3
  - Testing protocols above layer 4 (e.g., HTTP, etc.)
    - Instead, use load testing tools
  - Fuzzing
    - Instead, use: syzkaller

packetdrill scripting language: design goals

- Interpreted
  - For fast edit/test cycles (no make/compile/link/scp required)
  - Even on production machines w/o build tools
- Easy to write/ read for kernel network stack developers accustomed to...
  - Writing/reading **C code**
  - Looking at **strace** dumps to understand application system call interactions w/ the kernel
  - Looking at **tcpdump** traces to understand network stack behavior on the wire
- Feasible to turn strace + tcpdump traces from production into test cases
- Encourage simple, succinct tests
  - Encourages each script to be simple and easy to write and read
  - A description of one simple scenario
  - No conditionals, loops, or variables

packetdrill scripting language: design elements

- Comments
- System calls
- Packets
- Shell commands
- Python scripts

packetdrill: comments

- Comments
  - Document the intent for readers/maintainers
- Syntax:
  - C or C++ syntax

Examples:

```
/* C-style comments work */
// C++-style comments work
```

packetdrill: system calls

- System calls: strace-like syntax
  - system calls to invoke
  - output/return value to expect
  - blocking or non-blocking (only one blocking system call at a time)
- Syntax:
  - strace-like syntax

Example:

```
setsockopt(3, SOL_SOCKET, SO_REUSEADDR, [1], 4) = 0
```

packetdrill: packets

- Packets: tcpdump-like syntax
  - inbound packets to construct and inject into the network stack under test
  - outbound packets to expect and sniff and verify wrt timing and contents
  - TCP, UDP, ICMP
- Syntax:
  - tcpdump-like packet syntax prefixed by a pipe-inspired < (inbound) or > (outbound) specifier

Examples:

Inbound (inject):

```
< S 0:0(0) win 32792 <mss 1000,nop,nop,sackOK,nop,wscale 6>
```

Outbound (expect/sniff/verify):

```
> S. 0:0(0) ack 1 <mss 1460,nop,nop,sackOK,nop,wscale 7>
```

packetdrill: shell commands

- shell commands
  - To configure or inspect the machine under test
  - May use: ip, sysctl, tc, set device/module parameters ...
- Syntax:
  - Regular bash commands enclosed in single-tick quotes: ` `

Example:

```
`sysctl -q net.ipv4.tcp_congestion_control=cubic`
```

packetdrill: Python scripts

- Python scripts
  - Used to check/print internal socket state: TCP_INFO, TCP_CC_INFO, SO_MEMINFO
- Syntax:
  - Regular Python code enclosed in `%{ }%` braces
  - Can be multi-line scripts that assert, define and call Python functions, print output, etc.

Example:

```
%{ assert tcpi_snd_cwnd == 7 }%
```

packetdrill: specifying event times

- Every event in a packetdrill script starts with a time specifier: "when should this happen?"
- packetdrill allows flexibility in timing assertions
- Supported timing models:
  - Absolute: `0.100` `// event should happen 100ms since test start`
  - Relative: `+0.100` `// should happen 100ms since previous event`
  - Range: `0.100~0.200` `// should happen 100ms to 200ms since test start`
  - Relative range: `+0.100~+0.200` `// should happen 100ms to 200ms since previous event`
  - Wildcard: `*` `// test doesn't care; event can happen any time`
- Checking time:
  - Timing is critical for reliability and performance (loss recovery, congestion control, etc)
  - When a network stack event happens at an unexpected time, packetdrill raises a test failure
  - To avoid flakes, the default tolerance for timing variation: 4ms
  - Command line option to change the tolerance for all events (useful for debug or KASAN kernels):
    - `--tolerance_usecs=8000`
- blocking system calls
  - Provide a specified start and an expected end time separated by `...`
  - Syntax: `0.100...0.200`

packetdrill: setup and cleanup

- A test can use two special (optional) commands for **Setup** and **Cleanup**
  - If specified, they are always run, even if a test fails
  - They do not have a time specifier (their time is implicitly the start and end of the test, respectively)
  - Their execution is not timed, so can be as slow as it needs to be
- **Setup**:
  - Intended to set initial host / namespace configuration via: ip, tc, sysctl, etc...
- **Cleanup**:
  - Intended for checking behavior and cleaning up any changes made in setup
  - Always runs at test conclusion, even if test fails in the middle

Example:

```
// Setup: this test will specifically test reno congestion ctrl:
`sysctl -q net.ipv4.tcp_congestion_control=reno`

// ...timed system calls and packets to test reno...

// Cleanup: Now let's restore our state; always runs, even if test fails
`sysctl -q net.ipv4.tcp_congestion_control=cubic`
```

The packetdrill ellipsis construct: `...`

- `...` means "I don't care about this detail; just make it work"
  - Tells packetdrill to fill in boring boilerplate in the expected way to make things work
- Handy for several reasons:
  - 1: Eases writing of tests: you don't have to choose details to use (addresses, buffer contents)
  - 2: Eases reading of tests: you don't have to read unimportant details
  - 3: Allows scripts to be reused by being agnostic about details that can vary
    - Address family (AF_INET/AF_INET6) or addresses can vary

IP versions: ipv4, ipv6, ipv4-mapped-ipv6

- packetdrill supports 3 IP address family modes:
    - ipv4 AF_INET sockets, IPv4 packets and addresses
    - ipv6 AF_INET6 sockets, IPv6 packets and addresses
    - ipv4-mapped-ipv6 AF_INET6 sockets, IPv4 packets and addresses
- Specify the mode on the command line via --ip_version flag:
    - --ip_version=[ipv4,ipv4-mapped-ipv6,ipv6]
- Best practice: test scripts are written to be run in all 3 modes using `...`
    - All address-family-specific system call inputs/outputs are elided with `...`

```
0   socket(..., SOCK_STREAM, IPPROTO_TCP) = 3
+0  setsockopt(3, SOL_SOCKET, SO_REUSEADDR, [1], 4) = 0
+0  bind(3, ..., ...) = 0
+0  listen(3, 1) = 0
// SYN/SYNACK/ACK packets go here
+0  accept(3, ..., ...) = 4
```

Putting it all together...

- The following slide has a complete example packetdrill script
  - Testing loss recovery (fast recovery) and congestion control (CUBIC)
  - A typical packetdrill test for Linux TCP

```
Key:      BLACK: system call                              (strace syntax)
          BLUE:  input: incoming injected packet          (tcpdump-style syntax)
          RED:   output: outgoing sniffed packet          (tcpdump-style syntax)
          GREEN: Python script                            (Python code)
```

```
// Test Fast Recovery and CUBIC cwnd response to Fast Recovery.
`sysctl -q net.ipv4.tcp_congestion_control=cubic`  // shell command configures host

0   socket(..., SOCK_STREAM, IPPROTO_TCP) = 3             /* C-style comments work */
+0  setsockopt(3, SOL_SOCKET, SO_REUSEADDR, [1], 4) = 0 // C++-style comments work
+0  bind(3, ..., ...) = 0
+0  listen(3, 1) = 0
+0  < S 0:0(0) win 32792 <mss 1000,nop,nop,sackOK,nop,wscale 6>
+0  > S. 0:0(0) ack 1 <...>          // <...> means: don't care about outgoing options
+.1 < . 1:1(0) ack 1 win 257
+0  accept(3, ..., ...) = 4

+0  %{ assert tcpi_snd_cwnd == 10 }%  // check socket state from TCP_INFO
+0  write(4, ..., 4000) = 4000        // ask kernel under test to send 4 packets
+0  > P.  1:4001(4000) ack 1          // expect to sniff data pkts w/ these seqs/flags

+.1 < . 1:1(0) ack 1 win 257 <sack 1001:2001,nop,nop> // inject dupack #1
+0  < . 1:1(0) ack 1 win 257 <sack 1001:3001,nop,nop> // inject dupack #2
+0  < . 1:1(0) ack 1 win 257 <sack 1001:4001,nop,nop> // inject dupack #3
+0  > . 1:1001(1000) ack 1 // immediately after 3 dupacks we expect a fast retransmit!

+.1 < . 1:1(0) ack 4001 win 257                       // retransmit repaired loss
+0  %{ assert tcpi_snd_cwnd == 7 }%  // check CUBIC cwnd was cut by expected 30%
```

packetdrill local and remote modes

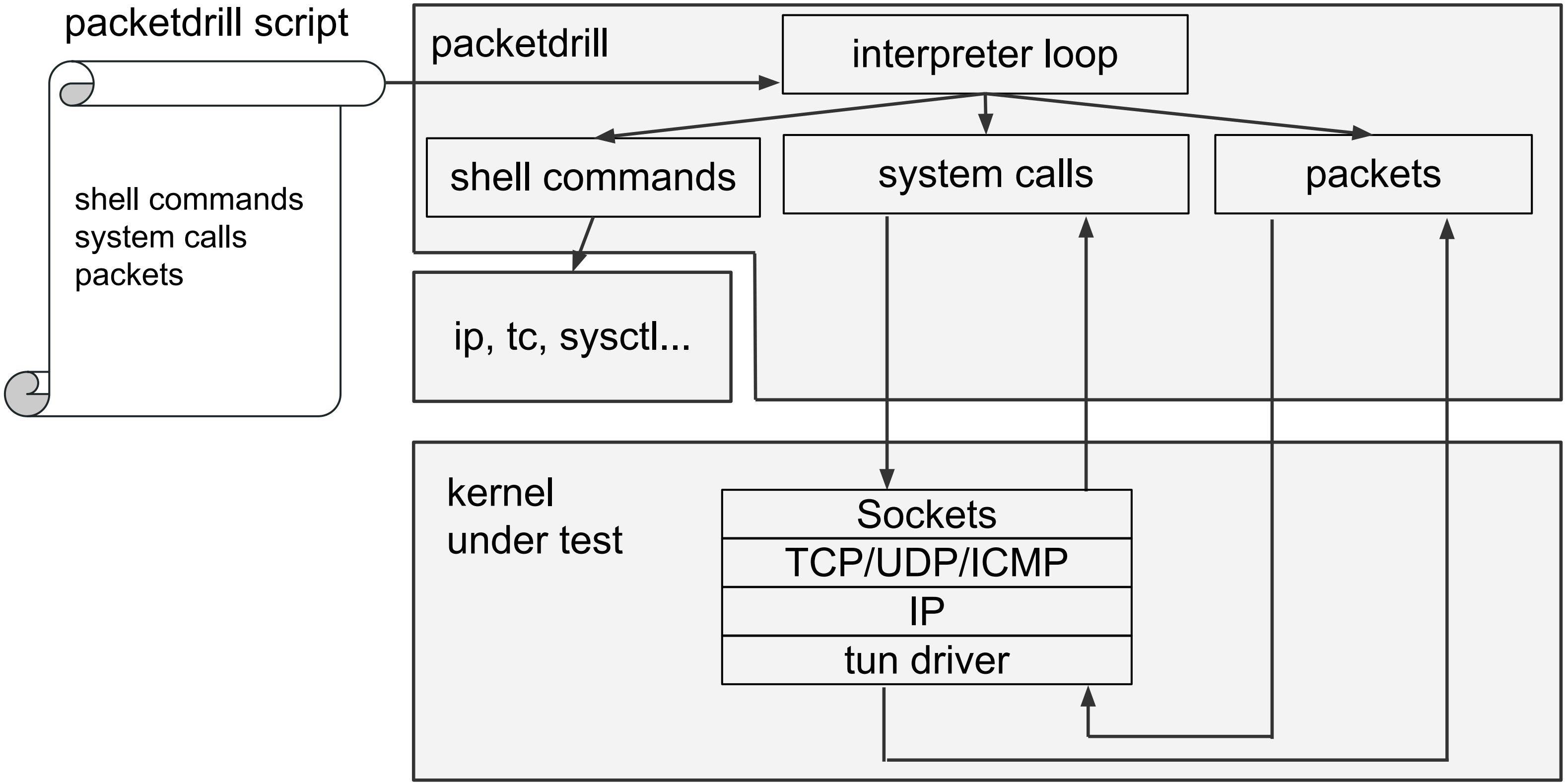
- Two execution models for testing network stack behavior:
  - **Local**: Within a single machine using a tun virtual network device (for speed and ease)
    - Single-machine testing using TUN virtual network device
      - Tests sockets, L4 (TCP/UDP/ICMP), L3 (IP)
    - A single packetdrill process
      - Runs system calls and shell commands
      - Injects packets via tun virtual network device, sniffs and verifies packets via tun
  - **Remote**: Over a physical NIC on a physical LAN (for testing real drivers and NICs)
    - Two-machine testing of real NICs over a LAN
      - Tests L4, L3, L2, L1, including driver, offload mechanisms, NIC, LAN
    - Machine 1: a client packetdrill process running on the kernel under test
      - Runs system calls and shell commands
    - Machine 2: a server packetdrill process running on a remote machine
      - Injects packets over real LAN, sniffs and verifies packets over real LAN

Running a packetdrill test in local mode

- Local mode is the default mode for test execution
- Run a packetdrill process as root on a single machine
- Need to provide:
  - The list of path names of script to execute
- Example:

```
test_machine# ./packetdrill foo.pkt
```

packetdrill local mode: design and implementation



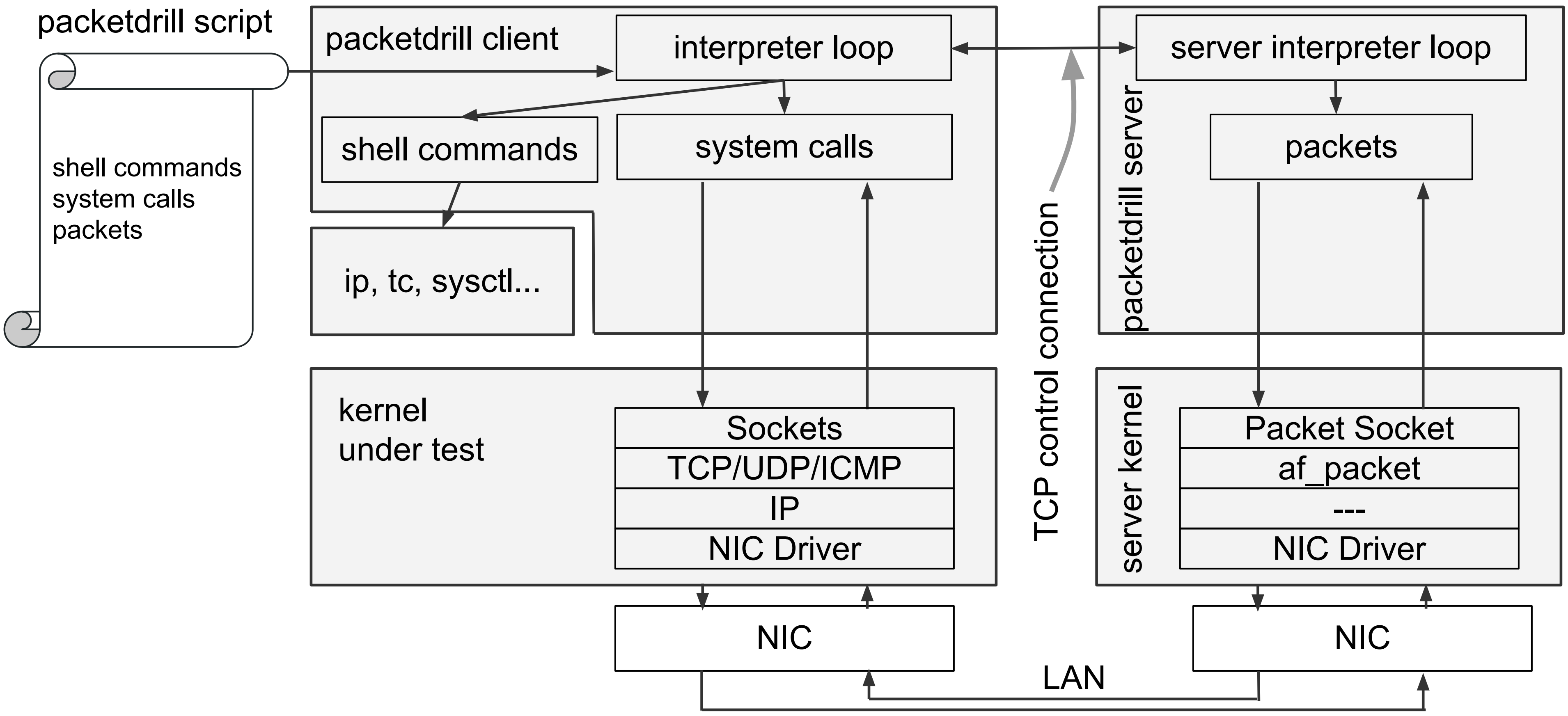
Running a packetdrill test in remote mode

- Remote mode requires an extra parameter for test execution
- Run a packetdrill process as root on two machines: a client and a server
- Need to provide:
  - The list of path names of script to execute
  - The DNS name or IP address of the server machine
- Example:

```
server_machine# ./packetdrill --wire_server

client_machine# ./packetdrill --wire_server_at=1.2.3.4 foo.pkt
```

packetdrill remote mode: design and implementation



Reusing scripts between local and remote mode

- The same test can be executed in both local mode and remote mode
- This works as long as network stack behavior asserted by test is the same
- Note: Sometimes MTU/MSS are different on different devices
  - Tests can often simply work around this with <...> to skip checking options
  - The earlier example script can run in both local and remote mode using this one weird trick

Part 2:
The basics of using packetdrill

Varieties of packetdrill

- There are several varieties/forks of packetdrill:
  - Original packetdrill by our team at Google:
    - https://github.com/google/packetdrill
  - Version with support for MPTCP, concurrent connections:
    - https://github.com/aschils/packetdrill_mptcp
  - The nplab packetdrill: supports UDPLite, SCTP, FreeBSD, MacOS:
    - https://github.com/nplab/packetdrill
  - A packetdrill for QUIC, at Apple:
    - 'Testing QUIC with packetdrill'
    - Unreleased (so far)

packetdrill test suites for Linux

- Current test suite status
  - In 2024 (Linux v6.12), 72 tests added to Linux tree (e.g. [tools/testing/selftests/net/packetdrill]())
  - 167 in Github at https://github.com/google/packetdrill
  - Over 1100 internally used by our team
    - For 13 years the Google Linux kernel networking team has used packetdrill scripts as a core part of continuous testing of the production kernel used on Google's machines
    - Gradually open-sourcing (Google => mainline) and porting (github => mainline)
- Example areas of coverage for Linux TCP ([gtests/net/tcp/]() subdirectories):

```
blocking          epoll              limited_transmit  sendfile          ts_recent
close             fast_recovery      md5               shutdown          user_timeout
common            fast_retransmit    mss               slow_start        validate
cubic             fastopen           mtu_probe         splice            zerocopy
cwnd_moderation   gro                nagle             syscall_bad_arg
ecn               inq                notsent_lowat     tcp_info
eor               ioctl              sack              timestamping
```

Downloading and building Google packetdrill

- First install the dependencies

```
sudo apt install git gcc make bison flex python net-tools  # for Debian/Ubuntu
```

- Then download the source code from https://github.com/google/packetdrill

```
git clone https://github.com/google/packetdrill.git
```

- Then build the packetdrill binary

```
cd ~/packetdrill/gtests/net/packetdrill

./configure

make
```

Running the github packetdrill test suite for Linux

- To run all tests in the packetdrill Linux test suite at https://github.com/google/packetdrill ...
- The easiest way is to use the run_all.py script by Willem de Bruijn:

```
cd ~/packetdrill/gtests/net/

sudo ./packetdrill/run_all.py -S -v -l tcp/
```

- This runs all test scripts with all 3 supported address families
  - ipv4, ipv6, ipv4-mapped-ipv6 (IPv6 sockets w/ IPv4 addresses)
- Explaining the command line options (see: ./packetdrill/run_all.py --help):
  - -S --serialized (run one test at a time; slower than parallel; avoids timing flakes)
  - -l --log_on_error (print stderr and stdout for failed tests)
  - -v --verbose (required for --log_on_error)

Main types of packetdrill errors

- Syntax errors
- Semantic errors (e.g., packet size doesn't match sequence number range)
- System call errors
    - Return value or completion time of blocking system call did not match expectations
- Packet errors
    - Contents or timing of outbound packet did not match expectations
    - Timed out waiting for outbound packet
- Shell command errors
    - Non-zero exit status (e.g., grep nstat output to check SNMP counter values)
- Python errors, including assertion failures
    - Show Python output and Python stack trace

How to interpret packetdrill test failures

- Packetdrill error message format:
  - <script_file_name>:<line_number>: <error_details>
- Example:

```
Script line:
+0  > . 3001:4001(1000) ack 1 // immediately after 3 dupacks we expect a fast retransmit!

Error:
test.pkt:21: error handling packet: live packet field tcp_seq: expected: 3001 (0xbb9) vs actual: 1 (0x1)
script packet:  0.200812 . 3001:4001(1000) ack 1
actual packet:  0.200808 . 1:1001(1000) ack 1 win 502
```

- How to interpret this error:
  - Script named test.pkt had an error on line 21
  - The script expected to sniff an outbound packet at time `0.200812` that looked like:
    - `. 3001:4001(1000) ack 1`
  - The network stack under test instead actually sent a packet at time `0.200808` that looked like:
    - `. 1:1001(1000) ack 1 win 502`
  - So basically the network stack sent a packet with an unexpected TCP sequence number range

Troubleshooting packetdrill test failures

- If a test fails, it can be useful to re-run and acquire more data
- 3 levels of detail can often be useful:
  - Run packetdrill with --verbose
    - Shows which system calls and packets happen, and when
    - Shows all variable values from TCP_INFO, etc, that are available in Python
  - Run packetdrill with --debug
    - Packetdrill shows function-level gory details
    - Useful for debugging packetdrill itself
  - Use strace on packetdrill and tcpdump in parallel
    - sudo tcpdump -n -i any port 8080 &
    - sudo strace -ttt --follow-fork packetdrill foo.pkt
      - -ttt for microsecond-level timestamps
      - --follow-fork to trace all threads

High-level advice for writing packetdrill tests

- Standard advice for writing unit tests applies...
- Add comments for future readers/maintainers (they will be debugging failures)
  - At top of file, explain what behavior is being tested/verified
  - Explain the key moments of stimulus/input: // Here we inject a special X packet ....
  - Explain the expected result: // Here we expect the kernel to send a Y packet because Z:
- Keep tests small and focused
  - And make test names clearly convey the functionality/scenario being tested
  - Eases review, maintenance, interpreting and root-causing failures
- Don't assert/check outside that focus (i.e., behavior test isn't focusing on)
  - e.g., only tests specifically for TCP receive window code should check receive window values
  - Minimizes/focuses toil/churn when the network stack behavior changes
- Make dependencies minimal and explicit
  - Avoid assuming specific config (receive buffer size, congestion control,...) because these vary
  - But if a test depends on something, set or check that explicitly

Best practices for configurations and network namespaces

- (1) Have a script to set config values you expect (sysctl / module parameters)
- (2) Run packetdrill tests inside a network namespace
  - Avoids tests accidentally changing global config parameters
  - Changing global config parameters can cause mysterious/hard-to-debug test failures
    - e.g., congestion control algorithm, receive buffer sizes, etc
- (3) Have explicit tests for the sysctl parameters you care about
  - There can be bugs (e.g., conflict resolution bugs) in simple code to initialize sysctl parameters
  - These can be hard to find if you are using (1)
  - So have tests that check:
    - Default global sysctl parameter values
    - Default values for per-netns sysctl values

Ways to integrate packetdrill into your workflow

- Can be useful:
  - Reproducing bugs or replaying traces
  - Testing what-if theories
  - git commit message documentation for bug fixes or feature additions
- Highly recommended:
  - Unit tests during network stack development (bug fixes, new features)
  - Running full regression suite before sending changes for review/merge
  - Automated continuous regression testing in a CI/CD pipeline (smp, debug, KASAN)

Contributing patches for packetdrill

- We are happy to incorporate fixes into packetdrill
  - And small-to-medium-sized features, as time permits!
- To contribute patches, please follow the recipe here; mainly:
  - Join the packetdrill mailing list on Google groups
  - Verify that you can certify the origin of your code with a Signed-off-by footer, according to the standards of the Linux open source project
  - Use scripts/checkpatch.pl from the Linux source tree to check the style of the C code
  - Please use a commit first/summary line like:
    - net-test: packetdrill: add new packetdrill support for foo
    - net-test: add new test cases for foo feature
  - Two ways to submit patches:
    - Github pull request
    - Use git commit/format-patch/send-email to the packetdrill mailing list on Google groups

Part 3:
Advanced packetdrill techniques

Tips on MSS and MTU

- Making tests work with all address families
  - Use --mtu=1520 with ipv6, since IPv6 headers are 20 bytes bigger
  - run_all.py handles this detail when running tests w/ all 3 address family modes
- For easy writing/reading of seq/ack, it's easiest to make MSS 1000

Tips on reducing timing flakes

- Use relative timestamps when possible
  - They avoid failures due to accumulating timing errors due to CPU / timer slowness
- Be careful with shell commands
  - They can take tens of milliseconds due to disk seeks, machine-wide synchronization, etc
  - So try to only use them in setup/cleanup blocks, which are untimed
- Be careful with exponential backoff in RTOs
  - Exponential backoff magnifies noise
  - Linux jiffy-granularity timers are up to 12.5% slower than you expect due to timer wheel impl
  - You may need to allow a relative range:
    - `+0.100~+0.200 // should happen 100ms to 200ms since previous event`

Defining symbols from command line with -D name=val

- Sometimes you want to reuse a test script with slight twists
  - e.g., some aspects of IPv4 and IPv6 differ beyond IP addresses
- packetdrill scripts can use generic symbols
- Invocations define macro-style symbols from command line with -D name=val
  - Much like: gcc -D name=val ...
- run_all.py includes some standard mappings; for example:

```
A script can use something like:
  cmsg_type=CMSG_TYPE_RECVERR,
  cmsg_data={ee_errno=ENOMSG,

For IPv4 run_all.py invokes packetdrill with:
  -D CMSG_LEVEL_IP=SOL_IP -D CMSG_TYPE_RECVERR=IP_RECVERR

For IPv6 run_all.py invokes packetdrill with:
  -D CMSG_LEVEL_IP=SOL_IPV6 -D CMSG_TYPE_RECVERR=IPV6_RECVERR
```

Testing ICMP with packetdrill

- Useful for testing how TCP and UDP deal with incoming ICMP errors
- For example, testing how TCP handles packets that are too big:

```
// TCP/IPv4 PMTU discovery:
   +0 write(4, ..., 1460) = 1460
   +0 > P. 1:1461(1460) ack 1
// ICMP says that segment was too big:
+.005 < icmp unreachable frag_needed mtu 1200 [1:1461(1460)]
// TCP picks a packet size using the MTU from the message, and retransmits ASAP:
   +0 > P. 1:1461(1460) ack 1
```

```
// TCP/IPv6 PMTU discovery:
   +0 write(4, ..., 1460) = 1460
   +0 > P. 1:1461(1460) ack 1
// ICMP says that segment was too big:
   +0 < icmp packet_too_big mtu 1280 [1:1461(1460)]
// TCP picks a packet size using the MTU from the message, and retransmits ASAP:
   +0 > P. 1:1461(1460) ack 1
```

Testing UDP with packetdrill

- Useful for testing how UDP deals with MTU, incoming ICMP errors, TOS, etc.
- For example:

```
// Create and connect a UDP socket:
    0 socket(..., SOCK_DGRAM, IPPROTO_UDP) = 3
 +.01 connect(3, ..., ...) = 0
   +0 getsockopt(3, IPPROTO_IP, IP_MTU, [1500], [4]) = 0

// Send the biggest possible UDP/IPv4 packet (without fragmentation).
   +0 write(3, ..., 1472) = 1472
   +0 > udp (1472)

// Check behavior with an MTU of net.ipv4.route.min_pmtu = 552 (512 + 20 + 20)
 +.01 < icmp unreachable frag_needed mtu 552 [udp (1472)]

// Verify we get an EMSGSIZE upon read() and can also read incoming packets:
 +.01 < udp (1472)
   +0 read(3, ..., 2000) = -1 EMSGSIZE (Message too long)
   +0 read(3, ..., 2000) = 1472
```

Encapsulation

- packetdrill can inject/sniff any combo of several common encap formats:
  - IPv4, IPv6, GRE, MPLS
- Syntax: separate encap header specs with : (colon) characters
- Examples:

```
// IPIP encap:
+0 > ipv4 1.1.1.1 > 2.2.2.2 : . 1:1001(1000) ack 1
// Double IPv6 encap:
+0 > ipv6 1::1111 > 2::2222: ipv6 3::3333 > 4::4444: . 1:1001(1000) ack 1
// Simple IPv4/GRE encap:
+0 > ipv4 1.1.1.1 > 2.2.2.2: gre: . 1:1001(1000) ack 1
// GRE encap with all GRE header fields specified:
+0 < ipv4 2.2.2.2 > 1.1.1.1 :
      gre flags 0xb000, sum 511, off 1023, key 0x80001234, seq 512 :
      . 1:1001(1000) ack 1 win 123
// GRE plus 2-entry MPLS encap:
+0 < ipv4 2.2.2.2 > 1.1.1.1 : gre :
     mpls (label 0, tc 0, ttl 0) (label 1048575, tc 7, [S], ttl 255) :
     . 1:1001(1000) ack 1 win 123
```

ECN: Explicit Congestion Notification

- packetdrill allows specifying the 2-bit ECN field in packets
- Useful for testing various flavors of ECN: Classic, DCTCP, L4S
- Syntax:

`[noecn]`	IP ECN field is 00; Not-ECT	sender transport (e.g., TCP) does not support ECN
`[ect0]`	IP ECN field is 10, ECT(0)	sender indicates “ECN-Capable Transport” (Classic)
`[ect1]`	IP ECN field is 01, ECT(1)	sender indicating “ECN-Capable Transport” (L4S)
`[ce]`	IP ECN field is 11, CE	set by network element to say “Congestion Experienced”

Example: injecting a packet with CE

```
+0 < [ce] P. 4001:4501(500) ack 3 win 257
```

Other IP header fields: TOS, flowlabel, TTL

- Packetdrill can set and check other interesting IP header fields...
- `tos`: ToS / QoS / DSCP / Traffic Class (packetdrill uses `tos` for both IPv4 and IPv6)
  - Useful for testing rx or tx processing of ToS, e.g. ToS reflection

```
// Inject SYN with tos 0x80 and verify outgoing SYNACK reflects incoming TOS:
+.1 < (tos 0x80) S 0:0(0) win 32792 <mss 1000,sackOK,nop,nop,nop,wscale 2>
 +0 > (tos 0x80) S. 0:0(0) ack 1 <...>
```

- `flowlabel`: IPv6 flowlabel
  - Useful for testing outgoing flowlabel for PLB load balancing [SIGCOMM '22], Protective ReRoute [SIGCOMM '23]

```
// Verify outgoing flowlabel matches (or is different from) previous flowlabel:
+0 > (flowlabel 0x1) P. 1001:2001(1000) ack 1
```

- `ttl`: TTL / Hop Limit (packetdrill uses `ttl` for both IPv4 and IPv6)
  - Useful for testing rx or tx processing of TTL

```
// Inject packet with TTL 100
+0   < (ttl 100) . 1:1(0) ack 201 win 1000
```

Part 4:
Wrapping up

For more information about packetdrill

- The Google packetdrill README at: https://github.com/google/packetdrill
- packetdrill: Scriptable Network Stack Testing, from Sockets to Packets
    - 2013 USENIX ATC
- Drilling Network Stacks with packetdrill
    - Usenix ;login: October 2013
- packetdrill mailing list on Google groups

The future...

Some features/directions that seem useful (contributions are welcome!)...

- A "black box recorder" option that will, upon test failure, dump a timestamped log of all test activity
  - To speed troubleshooting, especially for failed tests in automated test runs
- Optional Integration with UML and "Time Travel Mode" (NetDev 0x14)
  - To speed testing by running test suite in user mode on simulated time instead of booting a kernel and running on wall clock time

Conclusions

- Our team finds packetdrill useful for automated unit tests for Linux networking
  - We hope you'll find it useful too!
- Some packetdrill tests are now in mainline Linux: tools/testing/selftests/
- Please join us to make things even better in this open source ecosystem:
  - Contributing features/fixes for packetdrill
  - Contributing to the suite of packetdrill tests for Linux networking
  - Helping port packetdrill tests from: github => mainline or Google => mainline
- Thanks!