UNIVERSITY OF CAMBRIDGE

P51(bis): High Performance Networked-Systems

Prof. Andrew W. Moore

Part 2

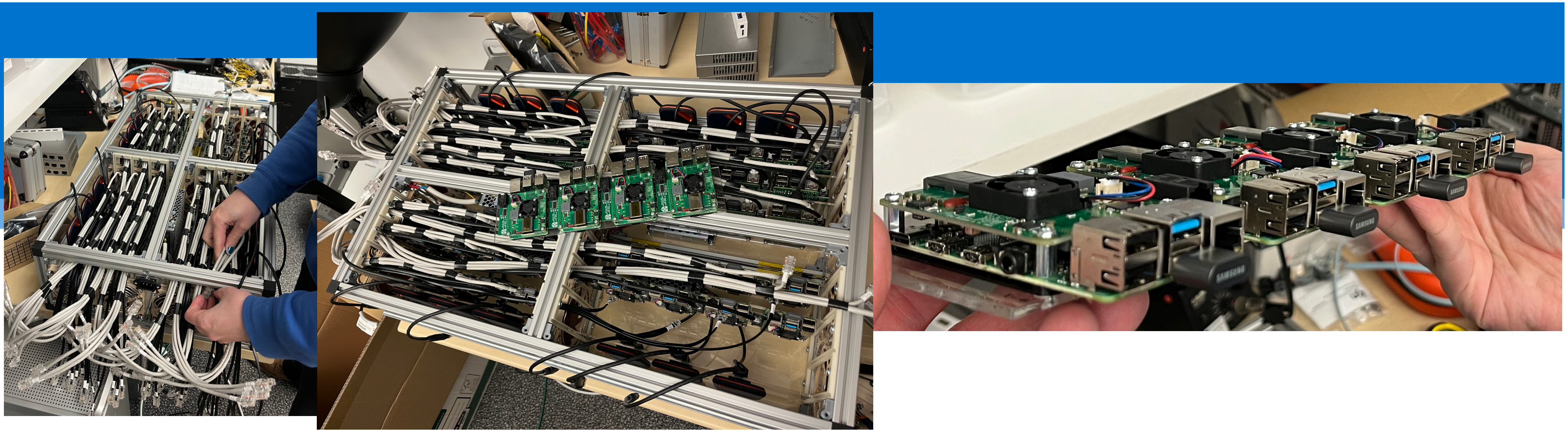
Finally, a **huge** thank you to Eben Upton, Raspberry Pi Foundation, and PiHut people for enabling this incarnation of the module at incredibly short notice.

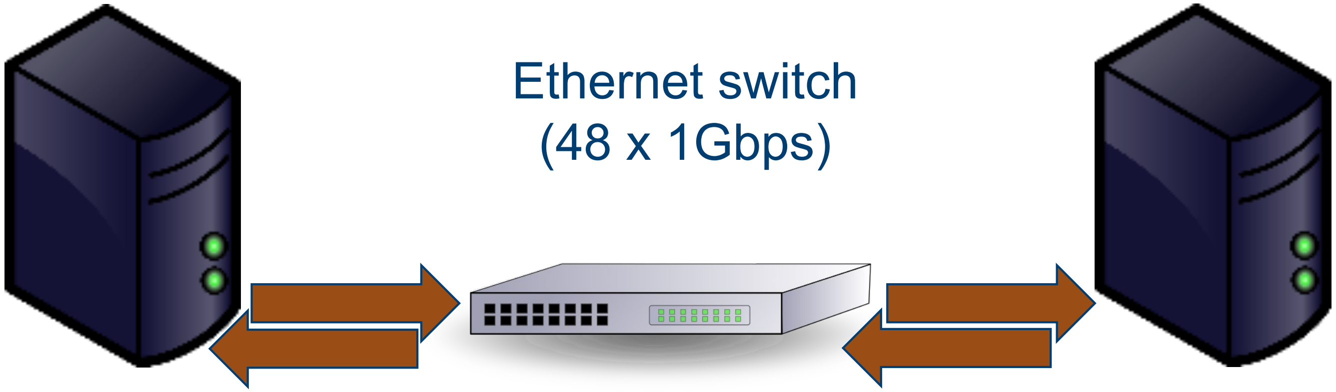
Lessons from Lab1

- Ping isn't the best tool for latency measurements
- Iperf isn't the best tool for bandwidth measurements

- Control, variability, accuracy, ….

- If you didn't conclude that; go back and look at your results….
- What should you expect? (do the math)



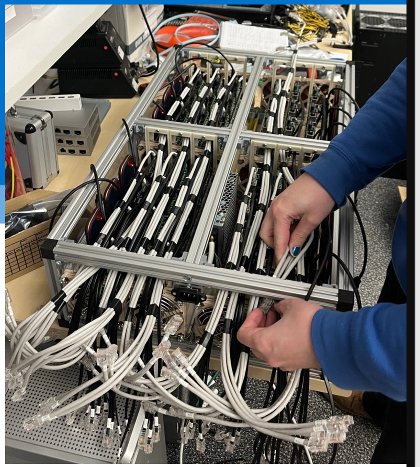


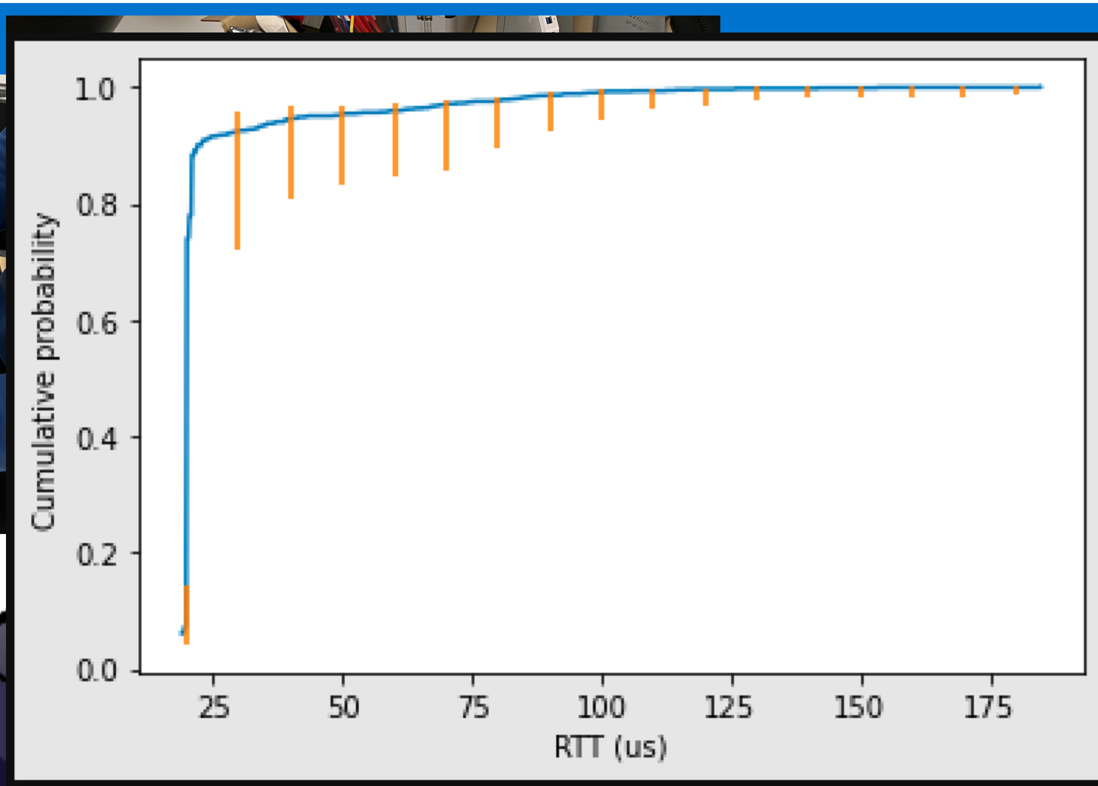
1m
Twisted pair (UTP)
1Gbps

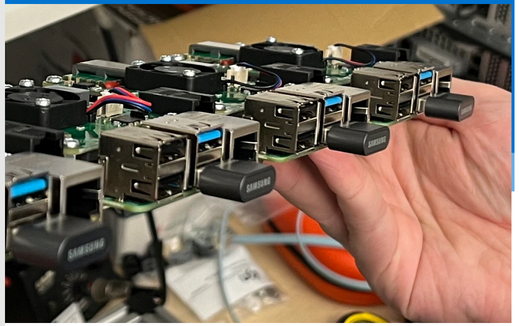
1m
Twisted pair (UTP)
1Gbps

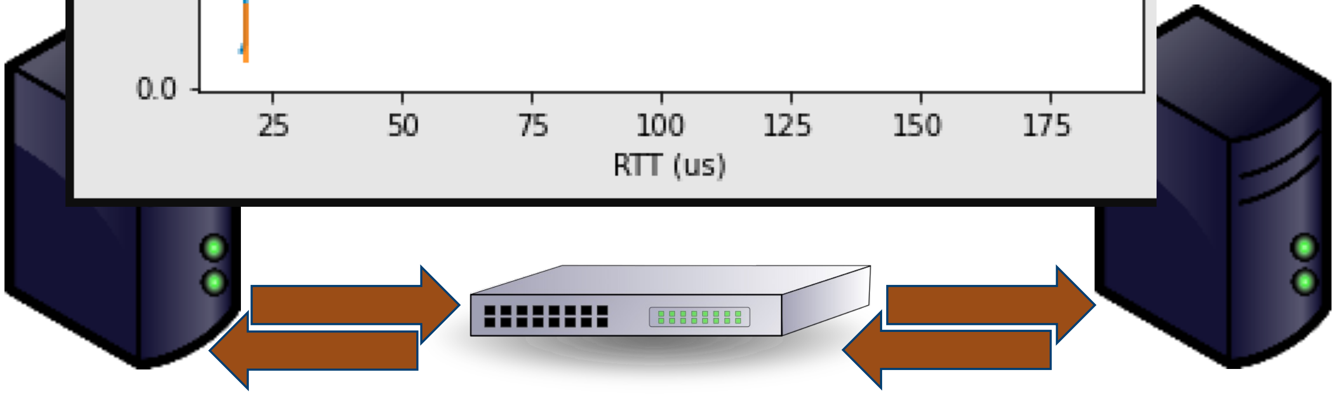
? Delay ? ? Delay ? ? Delay ? ? Delay ? ? Delay ?

<0.4ns Latency < 10 μs <0.4ns









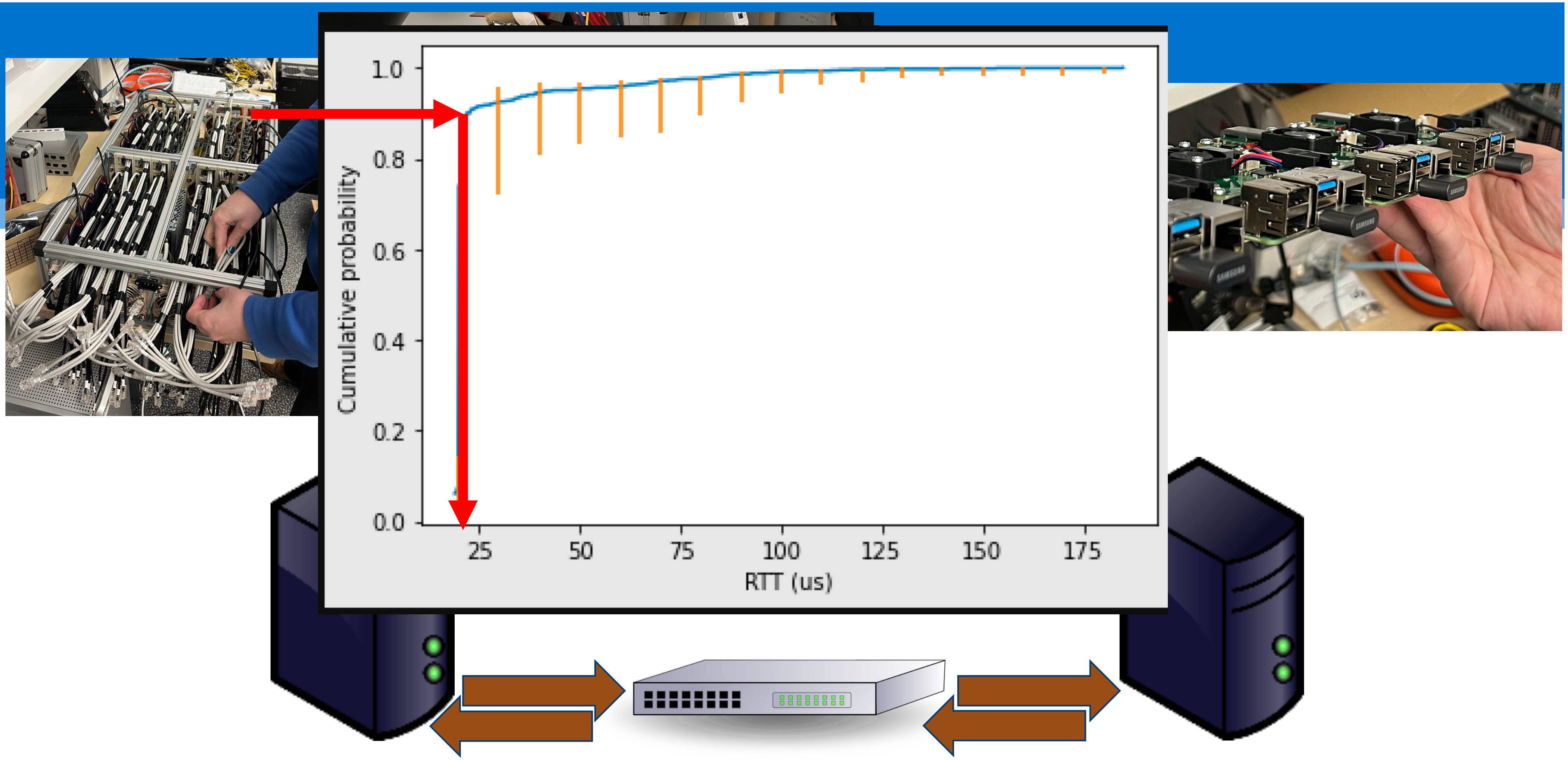
1m
Twisted pair (UTP)
1Gbps

<0.4ns

Latency < 10 μs

1m
Twisted pair (UTP)
1Gbps

<0.4ns



1m
Twisted pair (UTP)
1Gbps

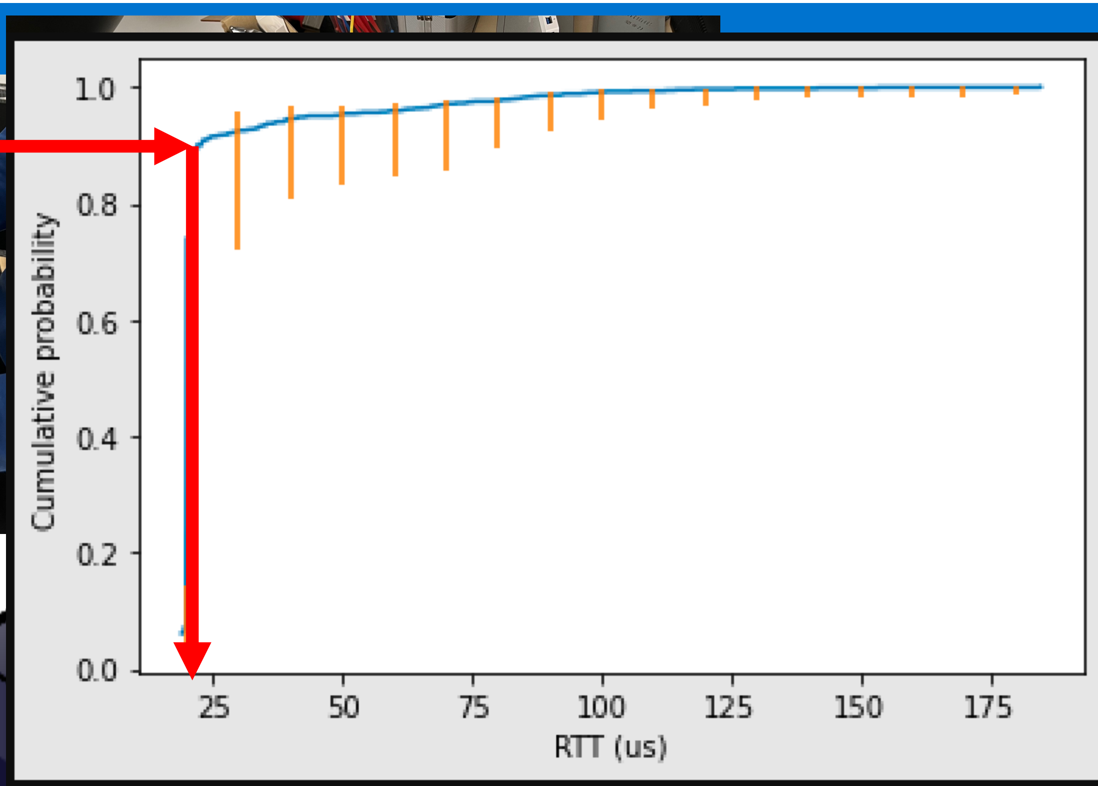
<0.4ns

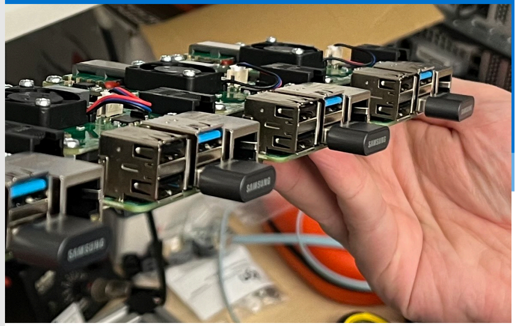
Latency < 10 μs

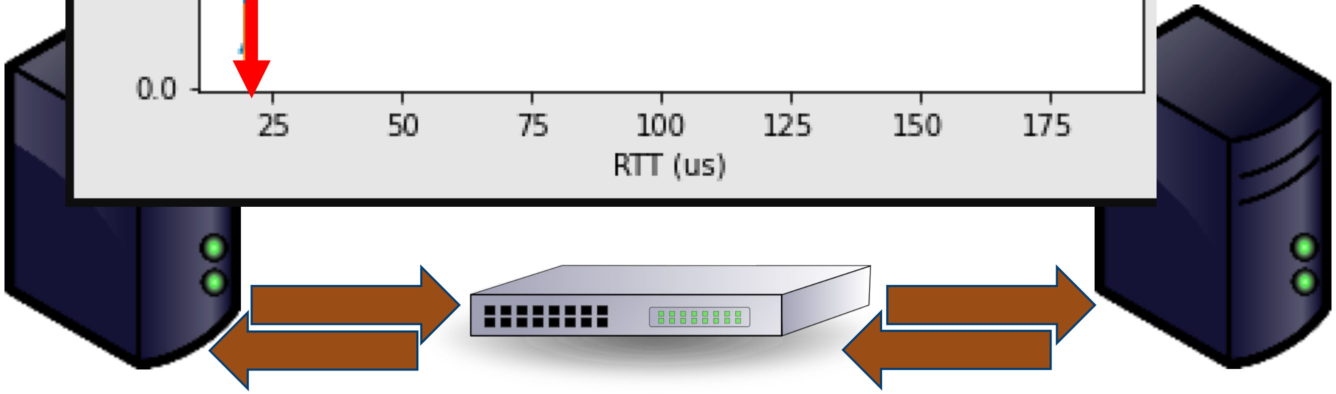
1m
Twisted pair (UTP)
1Gbps

<0.4ns

Ping reported ~90% results ~20 μs so ~2 x *switch*…. plus a bit….







1m
Twisted pair (UTP)
1Gbps

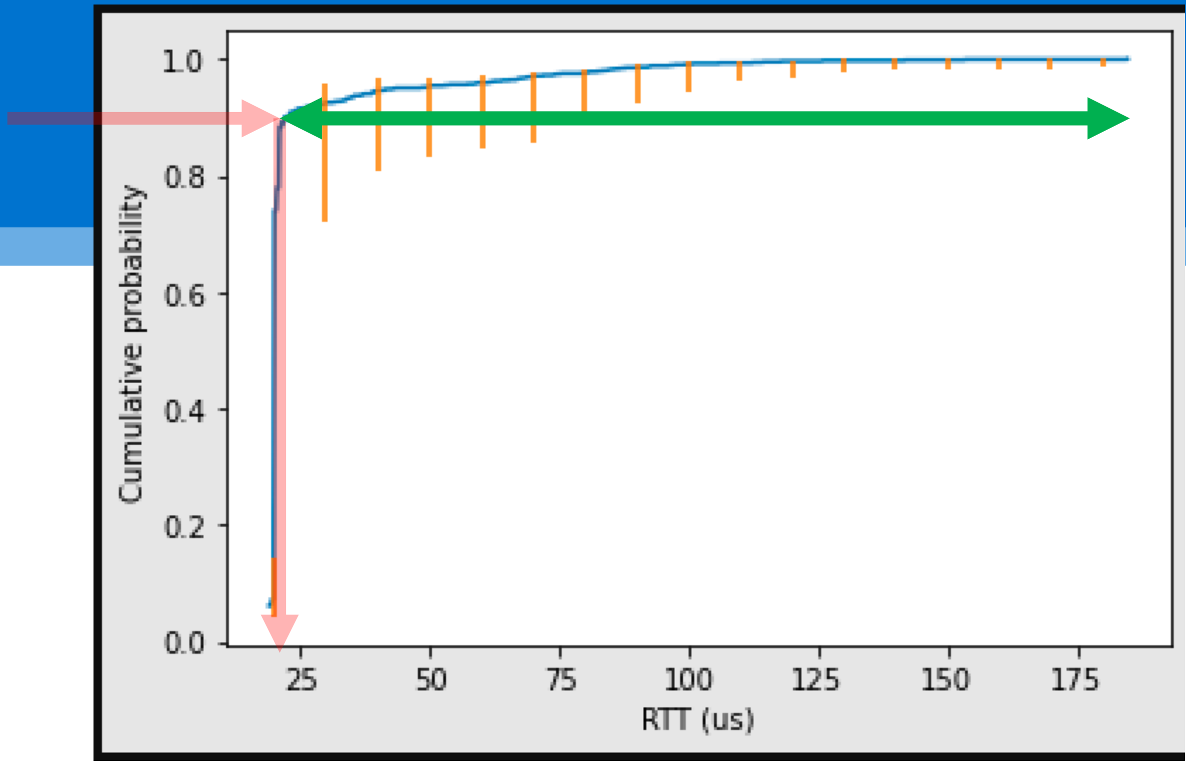
<0.4ns

Latency < 10 μs

1m
Twisted pair (UTP)
1Gbps

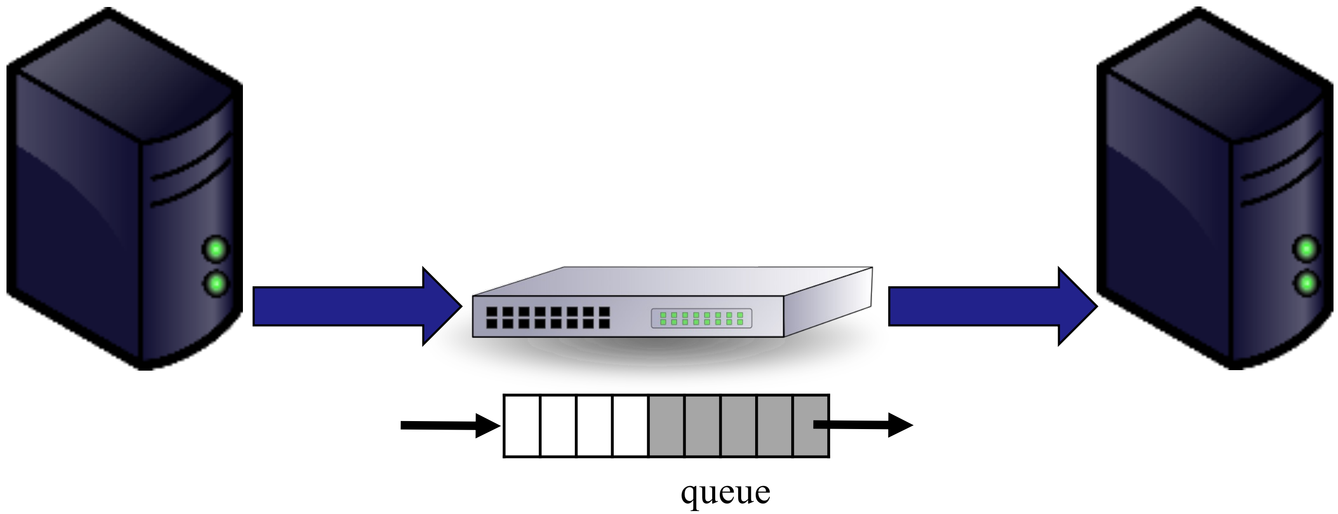
<0.4ns

Ping reported ~90% results ~20 μs   so ~2 x *switch*…. plus a bit….



- So even if the end hosts added no extra time (they do); what about the rest of the 150μs?
  - Systematic errors: clocks, speed of light
  - Non-systematic errors: scheduling in host, competing demands on resources,
    - BUFFERING in the switch
  - “Where has my time gone?” https://www.repository.cam.ac.uk/handle/1810/263038

Example: Network Congestion



How to control generated traffic?

- What is the packet format? (e.g. protocol, payload)
- How many packets?
- What is the packet size(s)?
- What is the average data rate?
- What is the peak data rate? (e.g. burst control)
- …

Traffic Generation Tools

$$$$$, Hardware, high quality
(Ixia, Spirent,..)

$$ Software/hardware based, medium quality
(OSNT, MoonGen,…)

Commodity, Software, low quality
(TCPReply,…)

TCP Replay

- Free, software-based
- Replays network traffic stored in pcap files
  - Not just TCP
  - (not just pcap)
- Included in Linux
- Packets are sent according to pcap file timestamps

Software based traffic generators

- Traditional tools (e.g., D-ITG, trafgen):
  - Rely on the interface provided by the kernel for packet IO
- Modern tools (e.g., MoonGen, pktgen, zsend):
  - Use special frameworks which bypass the network stack of an OS
  - Optimized for high speed and low latency
  - Cost: compatibility and support for high-level features

Measuring what happened.

- Recall: Active measurement (ping/iperf) &
  Passive measurement (tcpdump/intercept)

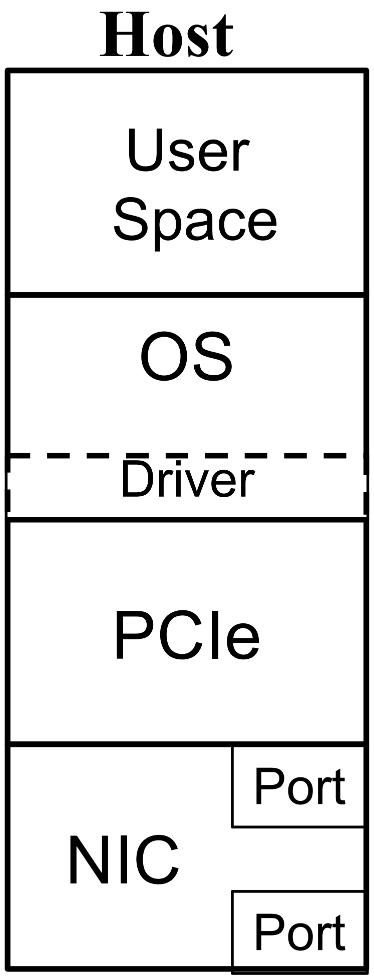
Passive measurement means we control the clocks, and we see what really happened (at least in one particular place)

How to capture traffic?

- When did the packet arrive?
  - A hard question!
- Can part / all of the packet be captured?
- How many packets can be captured?
- What is the maximal rate of packets that can be captured?
- …

What is the time?

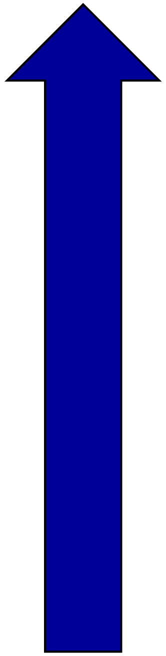
- Free running clocks, e.g.,
  - CPU's time stamp counter (TSC)
  - NIC's on board oscillator
  - Clocks drift!
- Synchronization signals, e.g.,
  - 1 PPS (pulse-per-second)
- Synchronization protocols, e.g.,
  - Network Time Protocol (NTP) – milliseconds accuracy
  - Precision Time Protocol (PTP) – microseconds accuracy (nanoseconds, depending on deployment)



Timestamping

- At the port – highest accuracy
  - If you want to measure *the network*
- At the NIC – less accurate
  - Buffering, clock domain crossing etc.
- At the OS
  - Exhibits PCIe effects, scheduling dependencies
- At the Application – least accurate
  - Unless you are interested in the user’s perspective – then it’s the ***only*** place

Traffic Capture



$$$$$, Hardware, high quality
(Ixia, Spirent,..)

$$ Software/hardware based, medium quality
(DAG, OSNT, NIC based,…)

Commodity, Software, low quality
(tcpdump, tshark, wireshark,…)

tcpdump (libpcap)

- Software only
- libpcap (historically tcpdump)
- Other applications: tshark, wireshark…
- Captures data and <does stuff> including write stuff to a file
- Uses the pcap format (and others…)
- Timestamp comes from the Linux network stack (default: kernel clock)

PCAP Files

- PCAP – **P**acket **CAP**ture
- libpcap file format
- Commonly used for packet capture/generation
- Format:

Global Header	Packet Header	Packet Data	Packet Header	Packet Data	Packet Header	Packer Data

- Global header: magic number, version, timezone, max length of packet, L2 type, etc.
- PCAP Packet header:

ts_sec	ts_usec	incl_len	orig_len

PCAP Files – a one slide outline

- PCAP – **P**acket **CAP**ture
- libpcap file format
- Commonly used for packet capture/generation
- Format:

Global Header	Packet Header	Packet Data	Packet Header	Packet Data	Packet Header	Packer Data

- Global header: magic number, version, timezone, max length of packet, L2 type, etc.
- PCAP Packet header:

ts_sec	ts_usec	incl_len	orig_len

Packet Capture

Common example:

- `$ sudo tcpdump -i en0 -tt -nn host www.cl.cam.ac.uk`

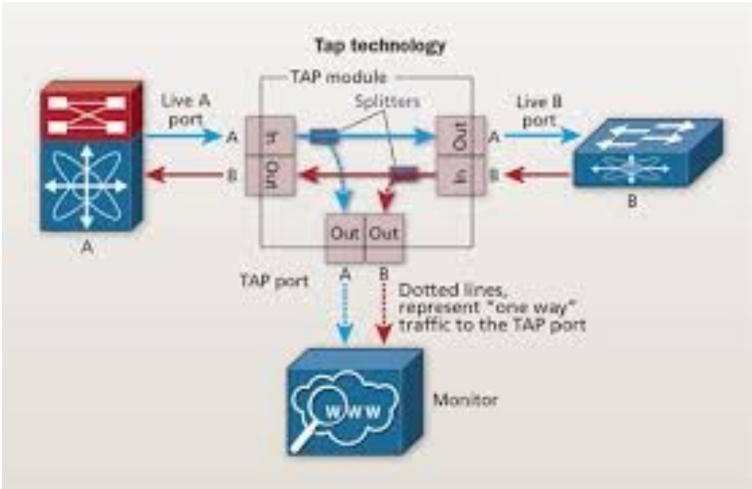
```
tcpdump: verbose output suppressed, use -v or -vv for full protocol decode
listening on en0, link-type EN10MB (Ethernet), capture size 65535 bytes
1507838714.207271 IP 192.168.1.107.50650 > 128.232.0.20.80: Flags [S], seq
3761395339, win 65535, options [mss 1460,nop,wscale 5,nop,nop,TS val 256908862 ecr
0,sackOK,eol], length 0
1507838714.207736 IP 192.168.1.107.50651 > 128.232.0.20.80: Flags [S], seq
527865303, win 65535, options [mss 1460,nop,wscale 5,nop,nop,TS val 256908862 ecr
0,sackOK,eol], length 0
….
```

Where do I trace?

- Sometimes on the interface of a host (eg ‘eth0’)
  - ➢ Tcpdump -i en1 # this will spew entries to the console one line per packet approximately
  - ➢ -tt -nn # useful options long form timestamps & numbers not names

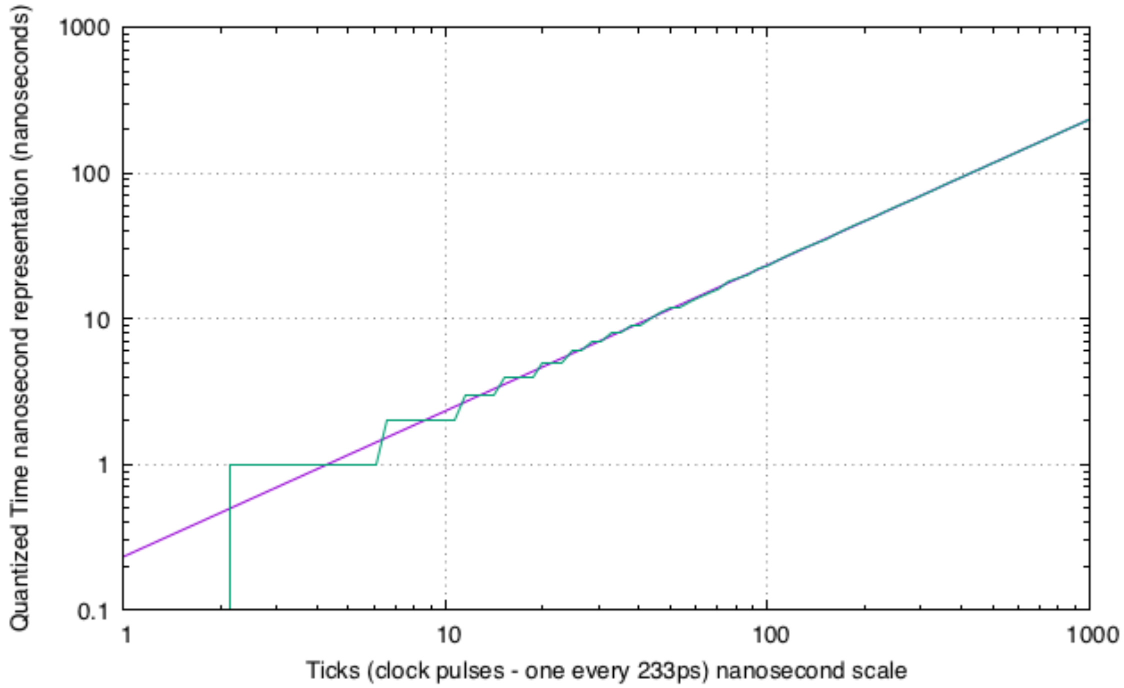
- Interception using “Tap”

  (think wire-**tap**ping)



Endace (DAG)

- DAG - Data Acquisition and Generation
- A commercial data capture card
- Packet capture at line rate
- Timestamping in the hardware (at the port)
- Nanosecond resolution
- Clock synronization possible
- Will be used in the labs



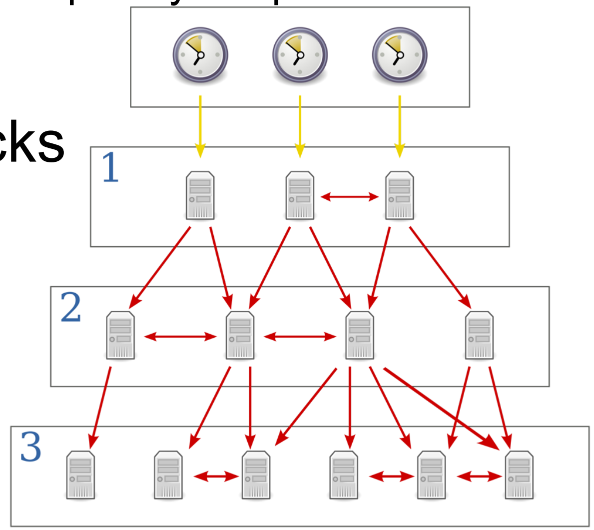
erf. binary dec
…..0001 232ps,
…..0010 466ps,
…..0011 698ps,
…..0100 931ps,
…..0101 1163ps,
…..0110 1397ps
…..0111 1629ps
…..1000 1862ps
erf = extensible record format

Why 232ps?

- Measuring (latency/change) between locations
  - Common time base: ntp? Ptp? GPS?
- Where do I measure?
  - Nic?
  - When the packet turns into useful work?
- Measuring inside the system (tracing a system)

NTP

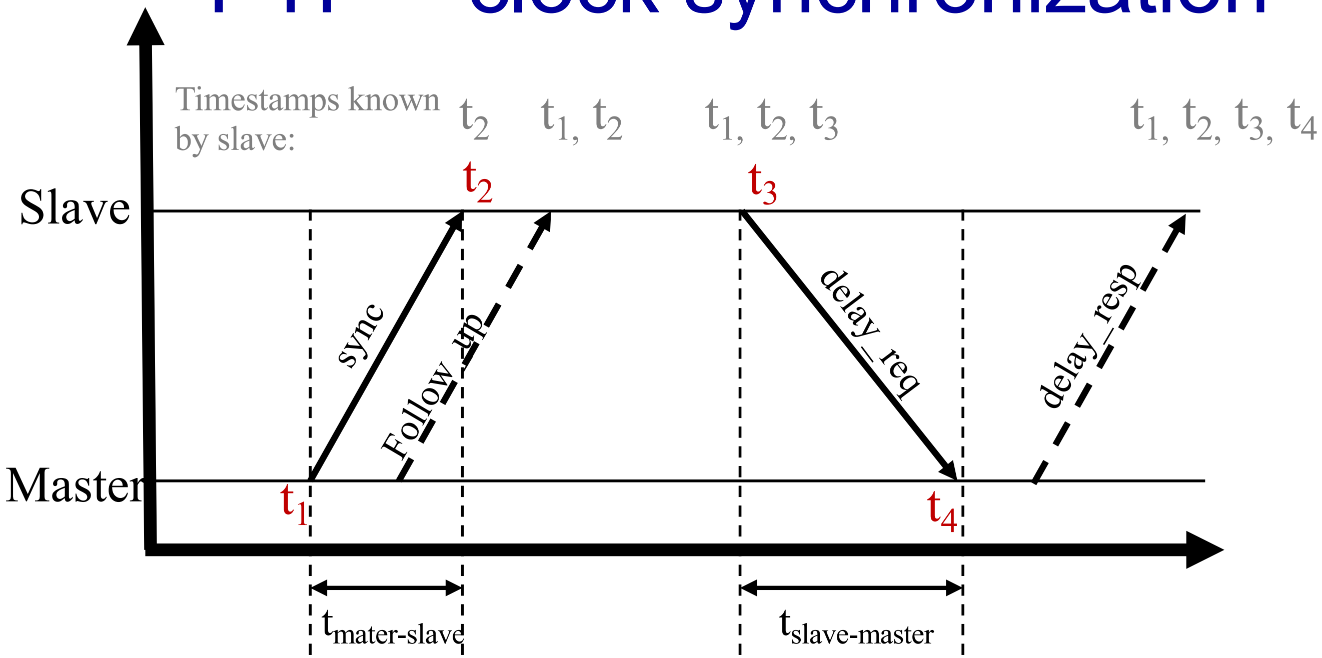
- Designed for Internet-scale synchronization
  - E.g., email sent time < email received time
  - Milliseconds scale – emphasises frequency not phase
- A hierarchical system
- Using a few reference clocks
- Typically:
  - Host polls a few servers
  - Compensates for RTT and time offset
  - NTPv4 – RFC5905



PTP

- IEEE standard 1588 (v2 – 1588-2008)
- Designed for local systems
  - Microsecond level accuracy or better
- Uses a hierarchical master-slave architecture for clock distribution
  - Grandmaster – root timing reference clock
  - Boundary clock – has multiple network connections, can synchronize different segments
  - Ordinary clock – has a single network connection (can be master or slave)
- (And many more details)

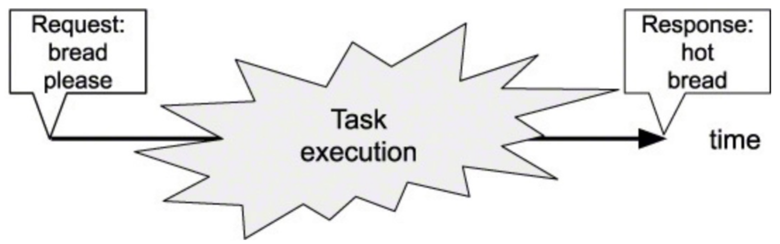
PTP – clock synchronization

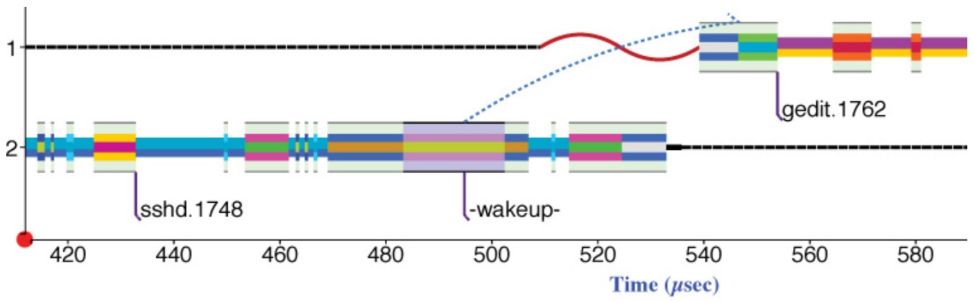


Offset $=(t_{mater\text{-}slave}-t_{slave\text{-}master})/2=t_{mater\text{-}slave}$-propagation time
mean propagation time $=(t_{mater\text{-}slave}+t_{slave\text{-}master})/2$

Using NIC

- Either implement PTP-derived timestamps
  or just timestamp the packets
  sometimes in hardware
  most times… not…
  Not all NICs support time stamping
- Result: captured packets include a timestamp
- If PTP is used, end hosts are synchronized
- Else – free running counter





- Taken from *Understanding Software Dynamics* R. Sites

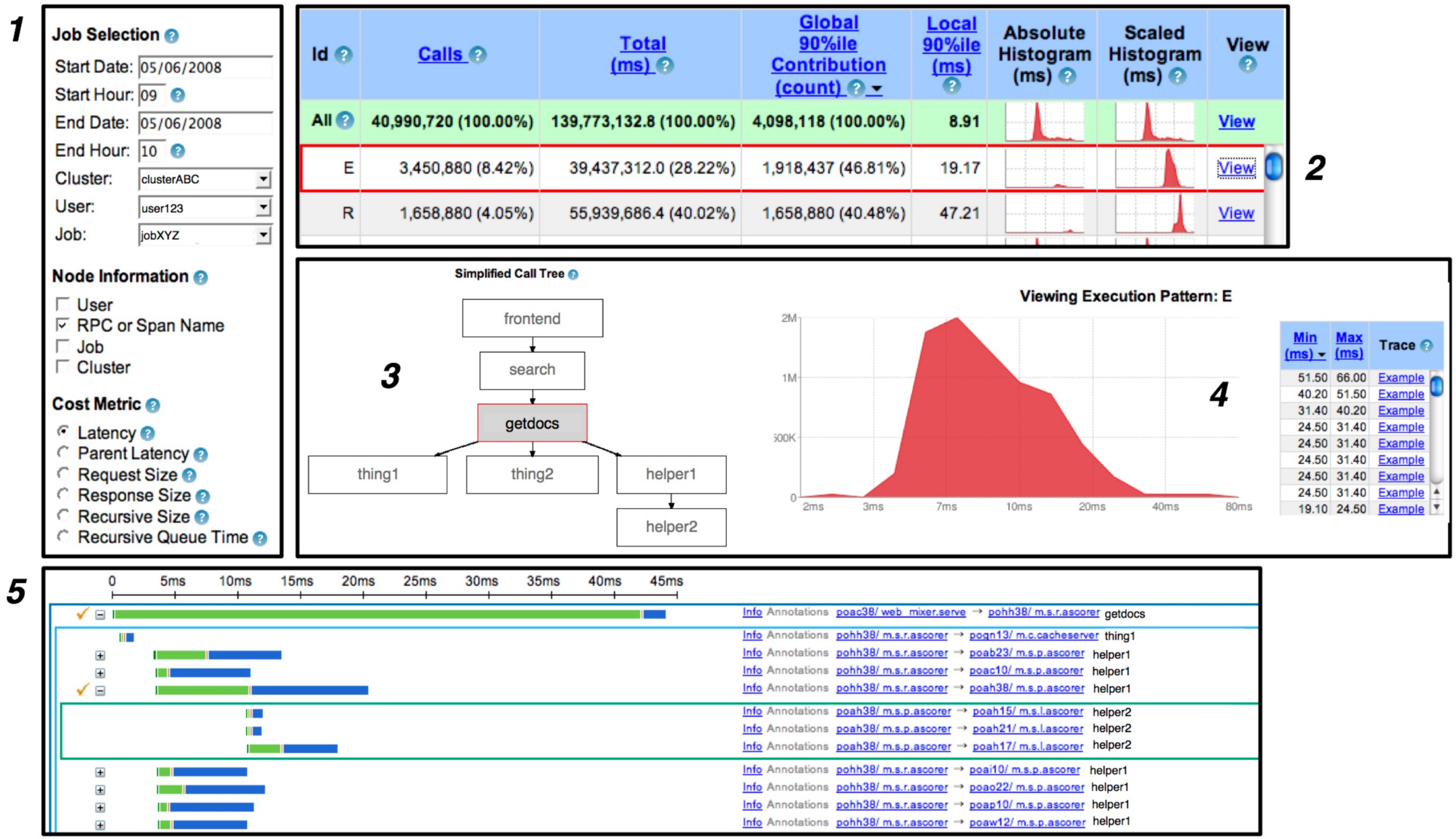


Figure 6: A typical user workflow in the general-purpose Dapper user interface.

- Taken from https://static.googleusercontent.com/media/research.google.com/en//archive/papers/dapper-2010-1.pdf

Capturing to disk…..

- Most (physical) disk systems can not capture 10Gb/s of data
- Capture takes resources!

- Format wars…. PCAP vs PCAP-ng vs others

- Binary representations / digital representations

What makes high-speed capture hard?

- Disk bandwidth
- Host bandwidth (memory, CPU, PCIe)
- Data management
- Lousy OS and software APIs
  - Byte primitives are dreadful when you want information on events, packets, & transactions…
  - A lot of effort has been invested into reinventing ring-buffers (circular buffers) to accelerate network interface cards.
  - Performance networking was done for capture first….

What makes high-speed capture work (better)?

- NVMe Disks
- Big machines, latest interfaces
- Collect metadata (version OS/system/hw/DNS)
- Bypass the OS
  - Older dedicated capture cards (e.g., Endace) pioneered kernel bypass capture
  - Any modern NIC 10Gb/s uses tricks that are useful for capture too

Measuring – Do’s and Don’t

- Make sure that you capture correctly
  - Disk, PCIe/DMA and other bottlenecks
- Make sure that your measurement does not affect the results
  - E.g., separate the capture unit from the device under test
- Understand what you are measuring
  - E.g. single host, application-to-application, network device etc.
- Make sure your measurement system does not affect the results

perf (not to be confused with iperf)

- So far we discussed *performance*
- What about *events?*
- Perf is a Linux profiler tool
- Allows us to instrument CPU performance counters, tracepoints and probes (kernel, user)

perf

- list – find events
- stat – count events
- record – write event data to a file
- report – browse summary
- script – event dump for post processing

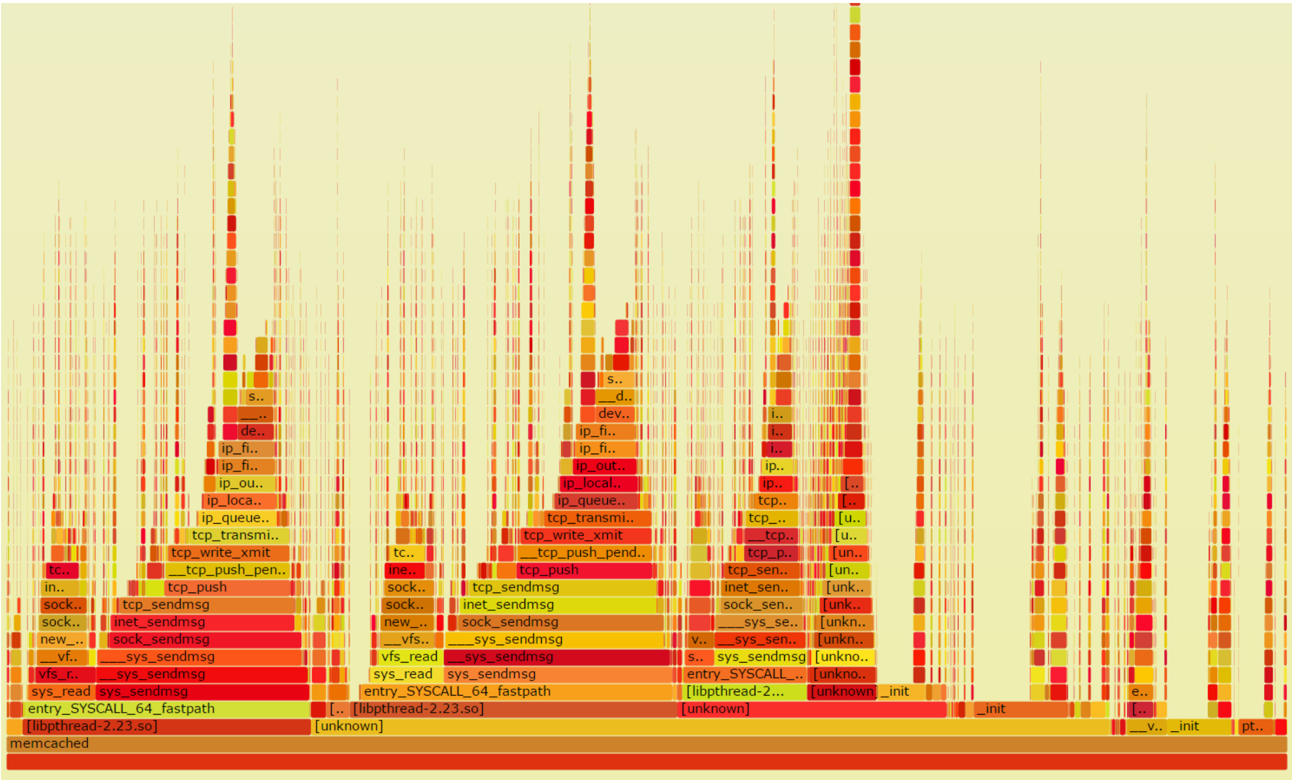
Perf - example

```
:~/.ssh$ perf stat ps
  PID TTY          TIME CMD
 8747 pts/2    00:00:00 bash
11667 pts/2    00:00:00 perf
11670 pts/2    00:00:00 ps

 Performance counter stats for 'ps':

         12.745507   task-clock (msec)         # 0.929 CPUs utilized
                 4   context-switches          # 0.314 K/sec
                 0   cpu-migrations            # 0.000 K/sec
               140   page-faults               # 0.011 M/sec
        32,322,489   cycles                    # 2.536 GHz                (40.80%)
   <not supported>   stalled-cycles-frontend
   <not supported>   stalled-cycles-backend
        27,644,922   instructions              # 0.86  insns per cycle    (68.86%)
         5,133,583   branches                  # 402.776 M/sec            (68.92%)
           157,503   branch-misses             # 3.07% of all branches    (94.06%)

       0.013726555 seconds time elapsed
```

the tool **scales** the count based on total time enabled vs time running

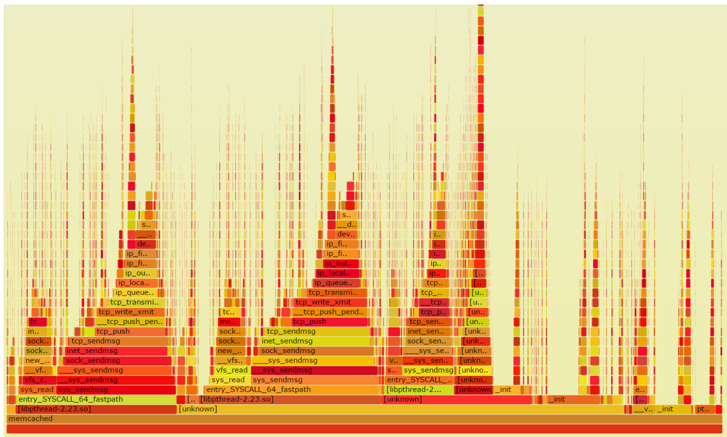
Flame Graphs: an example of clever visualization

- Parsing traces is like finding a needle in a haystack
- Flame graphs - Visualise the outputs of profiling tools
  - E.g., using perf, dtrace
- Easy to understand
- Open source
  - https://github.com/brendangregg/FlameGraph
  - Brendan Gregg has several other useful performance-related tools


memcached
[libpthread-2.23.so]
[unknown]
entry_SYSCALL_64_fastpath
sys_read
sys_sendmsg
___sys_sendmsg
__sys_sendmsg
sock_sendmsg
inet_sendmsg
tcp_sendmsg
tcp_push
__tcp_push_pending_frames
tcp_write_xmit
tcp_transmit_skb
ip_queue_xmit
ip_local_out
ip_output
vfs_read
[libpthread-2.23.so]
_init

Flame Graphs

- Width is relative to “how much time spent running on the CPU”
- Top-down shows ancestry
- Not good for idles – so don’t try to use for profiling network events!
- Different types of flame graphs
  - ➢ E.g. CPU, memory, differential



Conclusion

- There are many …. So so many …. tools
  each is shaped by its heritage
- Select carefully (understand the limitations)
- Consider and collect metadata – always
- How will you find/process/interpret/visualize your data?