The Network Stack (2)

L41 Lecture 6

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Reminder: Last time

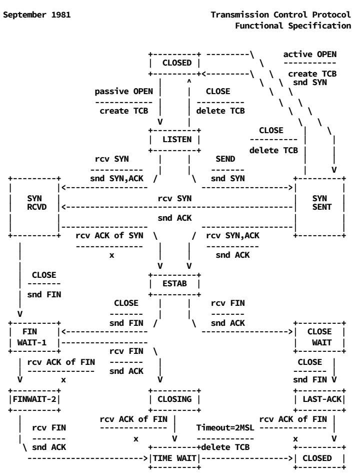
Rapid tour across hardware and software:

- Networking and the sockets API
- Network-stack design principles: 1980s and today
- Memory flow across hardware and software
- Network-stack construction and work flows
- Recent network-stack research

This time: The Network Stack (2)

- The Transmission Control Protocol (TCP)
  - The TCP state machine
  - TCP congestion control
  - TCP implementations and performance
  - The evolving TCP stack
  - Labs 4 + 5 on TCP
- Wrapping up the L41 lecture series

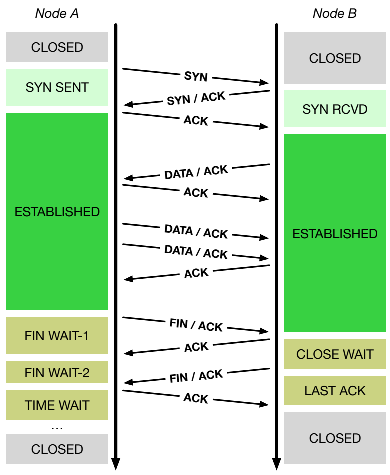
The Transmission Control Protocl (TCP)



TCP Connection State Diagram
Figure 6.

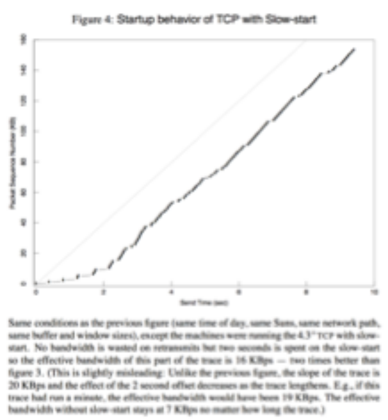
- V. Cerf, K. Dalal, and C. Sunshine, ***Transmission Control Protocol (version 1)***, INWG General Note #72, December 1974.
- In practice: J. Postel, Ed., ***Transmission Control Protocol: Protocol Specification***, RFC 793, September, 1981.

TCP principles and properties



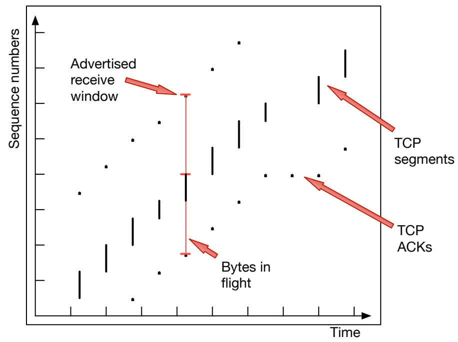
- Network may delay, (reorder), drop, corrupt packets
- TCP: Reliable, ordered, stream transport protocol over IP
  - Three-way handshake: SYN / SYN-ACK / ACK (mostly!)
  - Sequence numbers ACK'd
  - Round-Trip Time (RTT) measured to time out loss
  - Data retransmitted on loss
  - Flow control via advertised window size in ACKs
  - Congestion control ('fairness') detects congestion via loss

TCP congestion control and avoidance



- 1986 Internet CC collapse
  - 32Kbps → **40bps**
- Van Jacobson, SIGCOMM 1988
  - Don't send more data than the network can handle!
  - **Conservation of packets** via ACK clocking
  - Exponential retransmit timer, slow start, aggressive receiver ACK, and dynamic window sizing on congestion
- ECN (RFC 3168), ABC (RFC 3465), Compound (Tan, et al, INFOCOM 2006), Cubic (Rhee and Xu, ACM OSR 2008)

TCP time/sequence graphs



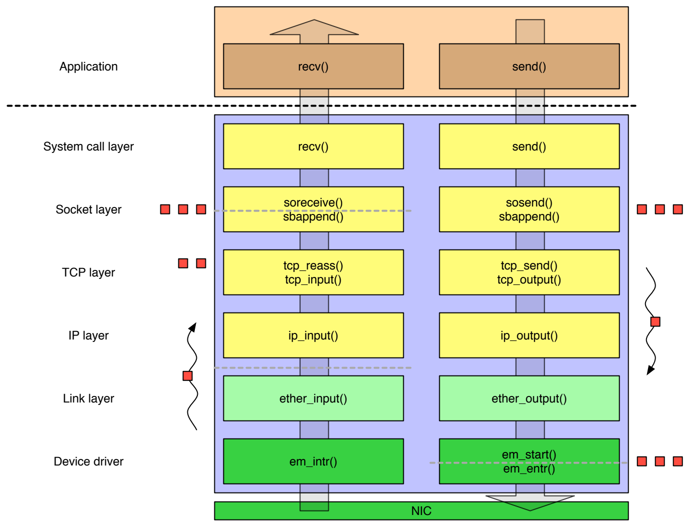
- Extracted from TCP packet traces (e.g., via `tcpdump`)
- Visualize windows, congestion response, buffering, RTT, etc:
  - X: Time
  - Y: Sequence number
- We can extract this data from the network stack directly using Dtrace
  - Allows correlation/plotting with respect to other variables / events

Evolving BSD/FreeBSD TCP implementation

Year	Version	Feature
1983	4.2BSD	BSD sockets, TCP/IP implementation
1986	4.3BSD	VJ/Karels congestion control
1999	FreeBSD 3.1	`sendfile(2)`
2000	FreeBSD 4.2	TCP accept filters
2001	FreeBSD 4.4	TCP ISN randomisation
2002	FreeBSD 4.5	TCP SYN cache/cookies
2003	FreeBSD 5.0-5.1	IPv6, TCP TIMEWAIT state reduction
2004	FreeBSD 5.2-5.3	TCP host cache, SACK, fine-grained locking
2008	FreeBSD 6.3	TCP LRO, TSO
2008	FreeBSD 7.0	T/TCP removed, socket-buffer autosizing
2009	FreeBSD 7.1	Read-write locking, full TCP offload (TOE)
2009	FreeBSD 8.0	TCP ECN
2012	FreeBSD 9.0	Pluggable TCP congestion control, connection groups

- Which changes have protocol-visible effects vs. only code?

Lect. 5 - Send/receive paths in the network stack



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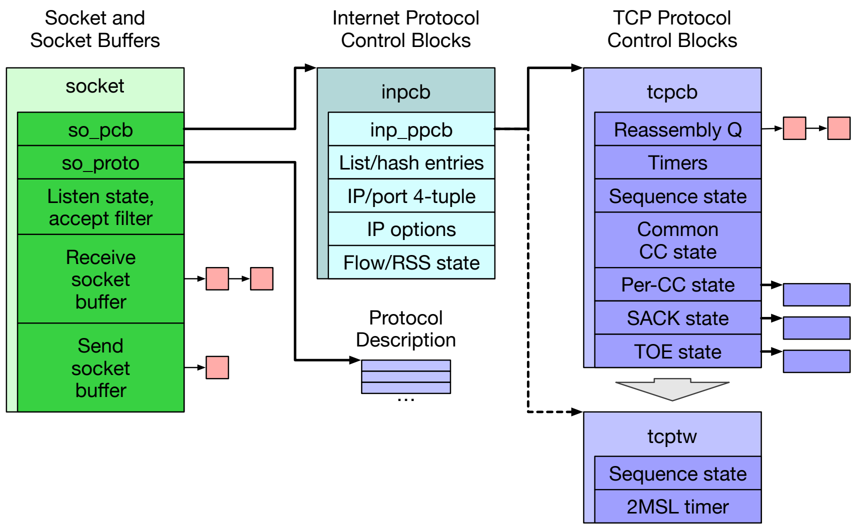
Data structures – sockets, control blocks



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Denial of Service (DoS) – state minimisation

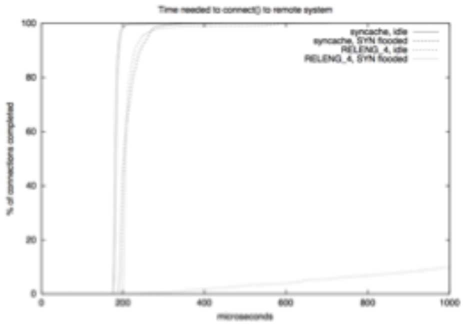
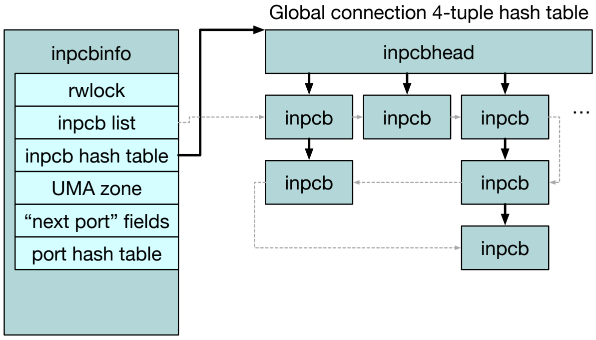


Figure 3: Time needed to connect() to remote system.

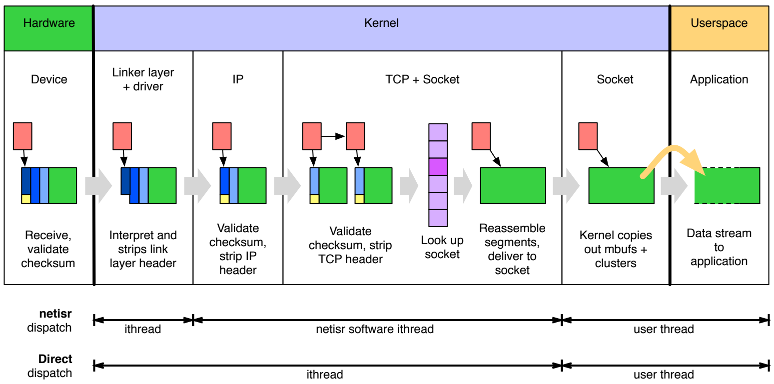
- Yahoo!, Amazon, CNN taken down by SYN floods in February 2000
- D. Borman: **TCP SYN cache** – minimise state for new connections
- D. Bernstein: **SYN cookies** – eliminate state entirely – at a cost
- J. Lemon: **TCP TIMEWAIT reduction** – minimise state during close
- J. Lemon: **TCP TIMEWAIT recycle** – release state early under load

TCP connection lookup tables



- Global list of connections for monitoring (e.g., netstat)
- Connections are installed in a global hash table for lookup
- Separate (similar) hash table for port-number allocations
- Tables protected by global read-write lock as reads dominate
  - New packets are more frequent than new connections

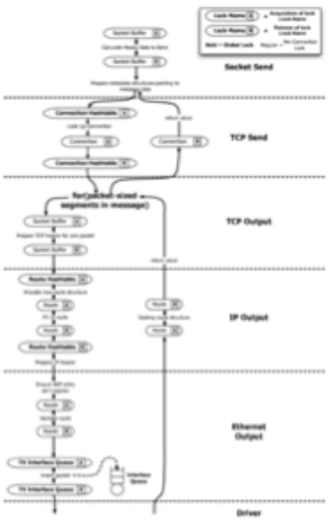
Lect. 5 - Work dispatch: input path



- **Deferred dispatch**: ithread → netisr thread → user thread
- **Direct dispatch**: ithread → user thread
  - Pros: reduced latency, better cache locality, drop early on overload
  - Cons: reduced parallelism and work placement opportunities

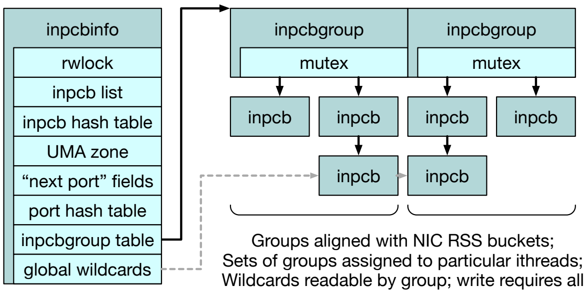
An Evaluation of Network Stack Parallelization Strategies in Modern Operating Systems

Paul Willmann, Scott Rixner, and Alan L. Cox, USENIX ATC, 2006



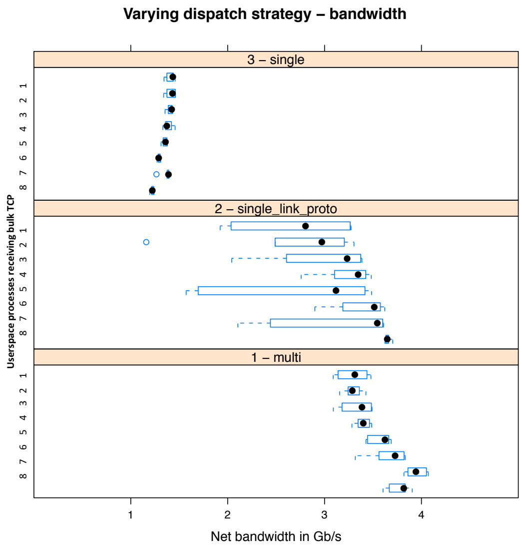
- Network bandwidth growth > CPU frequency growth
- Locking overhead (space, contention) substantial
  - Getting 'speedup' is hard!
- Evaluate different strategies for TCP processing parallelisation
  - Message-based parallelism
  - Connection-based parallelism (threads)
  - Connection-based parallelism (locks)
- Coalescing locks over connections:
  - reduces overhead
  - increases parallelism

FreeBSD connection groups, RSS



- **Connection groups** blend MsgP and ConnP-L models
  - PCBs assigned to group based on 4-tuple hash
  - Lookup requires group lock, not global lock
  - Global lock retained for 4–tuple reservation (e.g., setup, teardown)
- Problem: have to look at TCP headers (cache lines) to place work!
- Microsoft: NIC **Receive-Side Scaling (RSS)**
  - Multi-queue NICs deliver packets to queues using hash of 4-tuple
  - Align connection groups with RSS buckets / interrupt routing

Performance: dispatch model and locking



- 2010 8-core x86 multicore server
- TCP LRO disabled (maximise PPS)
- Configurations:
  - 1 queue (no dispatch), 1 thread on 1 core
  - 1 queue (SW dispatch), 8 threads on 8 cores
  - 8 queues (HW dispatch), 8 threads on 8 cores

Architectural → micro-architectural + I/O optimisation

- Hardware, software, protocol co-design causes change to optimisation approach over time:
  - Counting instructions → counting cache misses
  - Reducing lock contention → cache-line contention
  - Adding locking → identifying new parallelism

  - Work ordering, classification, and distribution
  - Vertically integrated distribution and affinity

  - NIC offload of further protocol layers, crypto
  - DMA/cache interactions
- Convergence of networking and storage technologies?

Labs 4 + 5: TCP

- From abstract to concrete understanding of TCP
  - Use tools such as `tcpdump` and `DUMMYNET`
  - Explore effects of latency on TCP performance
- Lab 4 – TCP state machine and latency
  - Measure the TCP state machine in practice
  - Start looking at TCP latency vs. bandwidth (`DUMMYNET`)
  - At what transfer sizes are different latencies masked?
- Lab 5 – TCP congestion control
  - Draw time-sequence-number diagrams
  - Explore OS buffering strategies
  - Explore slow-start vs. steady state as latency changes
  - Explore OS and microarchitectural performance interactions

L41 lecture wrap-up

- Goal: Deeper understanding of OS design and implementation
  - Evolving architectural and microarchitectural foundations
  - Evolving OS design principles
  - Evolving tradeoffs in OS design
  - Case study: The process model
  - Case study: Network-stack abstractions
  - Quick explorations of past and current research
- Goal: Gain practical experience analysing OS behaviour
- Goal: Develop scientific analysis and writing skills
- Feel free to get in touch to learn more!