Workshop on New Visions for Large-Scale Networks: Research & Applications
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The Future of High-Performance Networking

(The 5?, 10?, 15? Year Outlook)

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Outline

- History of Networking in High-Performance Computing (HPC)
  - TCP in HPC?
  - Current Solutions for HPC
- Future of High-Performance Networking: TCP vs. ULNI
  - The Road to a HP-TCP
    - What's Wrong with TCP?
    - Solutions?
- Crossroads for High-Performance Networking

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TCP for High-Performance Computing?

- Problems with TCP for HPC in the Mid-1990s   Today & Tomorrow
  - Computing Paradigm: *Cluster or supercomputer.*   + *computational grid*
  - Network Environment: *System-area network (SAN).*   + *wide-area network (WAN)*
  - ~~TCP Performance (mid-90s): *Latency: O(1000 µs). BW: O(10 Mb/s).*~~   Too heavywgt
  - TCP Performance (today): *Latency: O(100 µs). BW: O(500 Mb/s).*
  - TCP Performance (optimized): *Latency: 95 µs. BW: 1.77 Gb/s. [Trapeze TCP]*
- Solution   ➢ Problem: ULNIs do *not* scale to WAN. Must use TCP (despite conflicts).
  - User-level network interfaces (ULNIs) or OS-bypass protocols
    - Active Messages, FM, PM, U-Net. Recently, VIA (Compaq, Intel, µsoft)
  - ULNI Performance (mid-90s): *Latency: O(10 µs). BW: O(600-800 Mb/s).*
  - ULNI Performance (Reference: Petrini, Hoisie, Feng, Graham, 2000.)
    - *Latency: 1.9 µs.*   *BW: 392 MB/s = 3.14 Gb/s.*
    - *User-Level Latency: 4.5 µs.*   *User-Level BW: 307 MB/s = 2.46 Gb/s.*

Latency & BW problems *not* specific to HPC

- Medicine – M. Ackerman (NLM).
  - ECG: 20 GB *now* @ 100% reliability! Neurological: Smoothness @ 80% ok.
- Remote collaboration & bulk-data transfer – R. Mount (SLAC). 100 GB → 22 hrs.
- Integrated multi-level collaboration – T. Znati (NSF/ANIR).

Current Solutions for HPC

- Computational Grid (WAN) — Cost-effective for commodity, "high-end" supercomputing. Better fault tolerance than large-scale supercomputers.
  - TCP
    - \+ Infrastructure to deal with routing (ARP, IP).
    - o Congestion control (conflict between Internet & HPC communities).
    - – Non-adaptive flow control.
    - – High latency (even over short distances) and low bandwidth.

    } "Re-inventing" ULNI
- Cluster Computing or Supercomputing (SAN)
  - User-Level Network Interface (ULNI) or OS-Bypass Protocol
    - \+ Negotiated flow control.
    - \+ Low latency and high bandwidth.
    - – No automatic infrastructure to deal with routing.
    - – No congestion control.

    } "Re-inventing" TCP
- Each community is working to address the negatives.
  - Will each community continue as separate thrusts? Sociologically? Technically?

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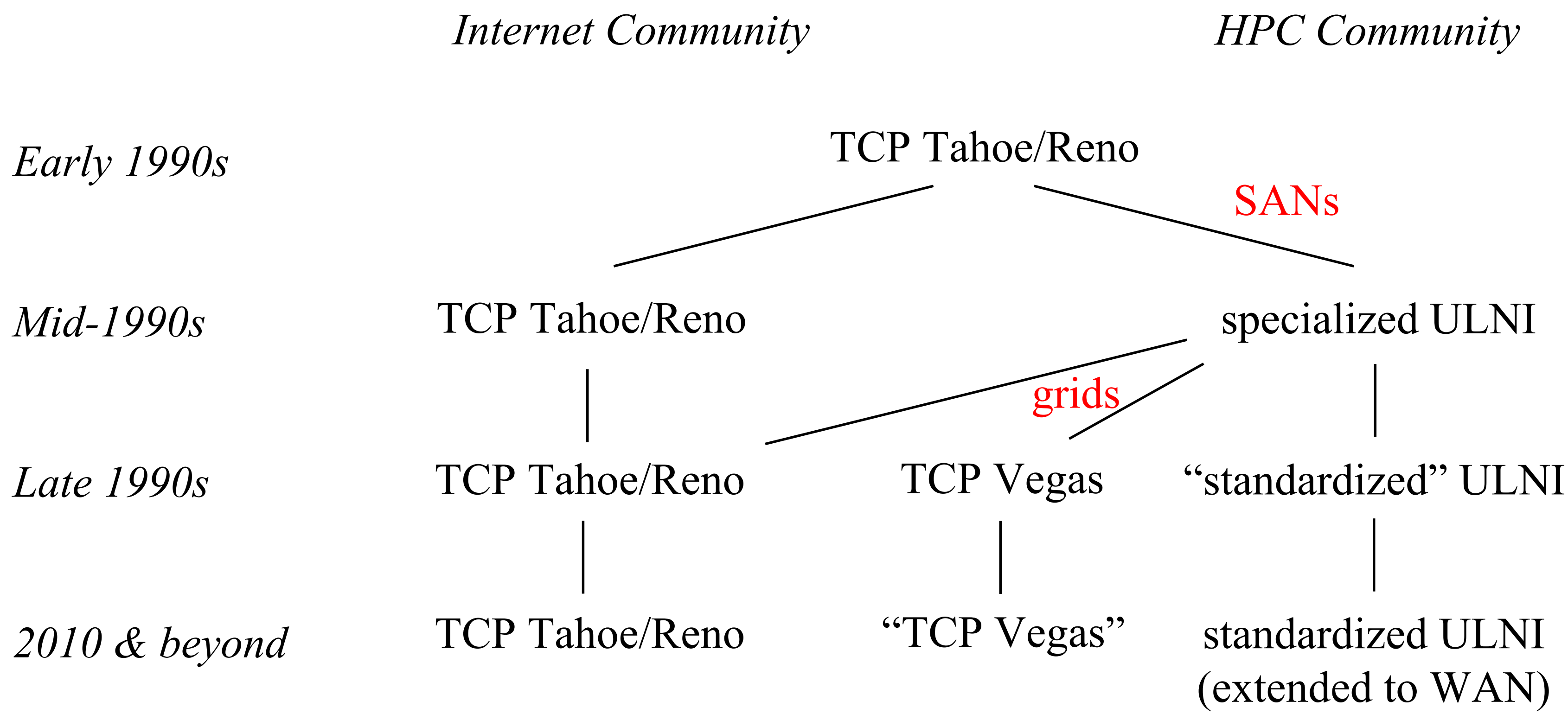
Future of High-Performance Networking



+ active queue management in network
(to ensure fairness)

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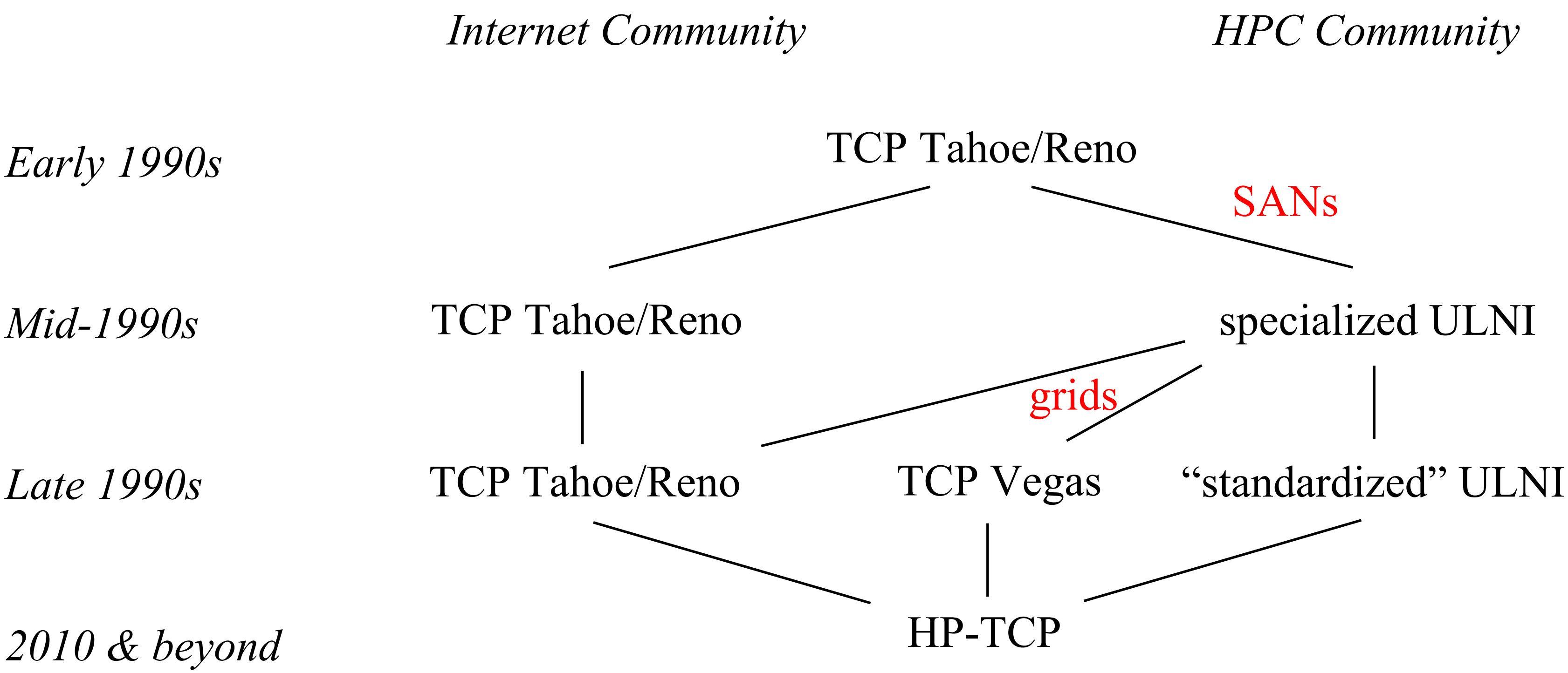
Future of High-Performance Networking



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The Road to a HP-TCP

10GigE packet interarrival: 1.2 µs
Null system call in Linux: 10 µs

What's Wrong with TCP?

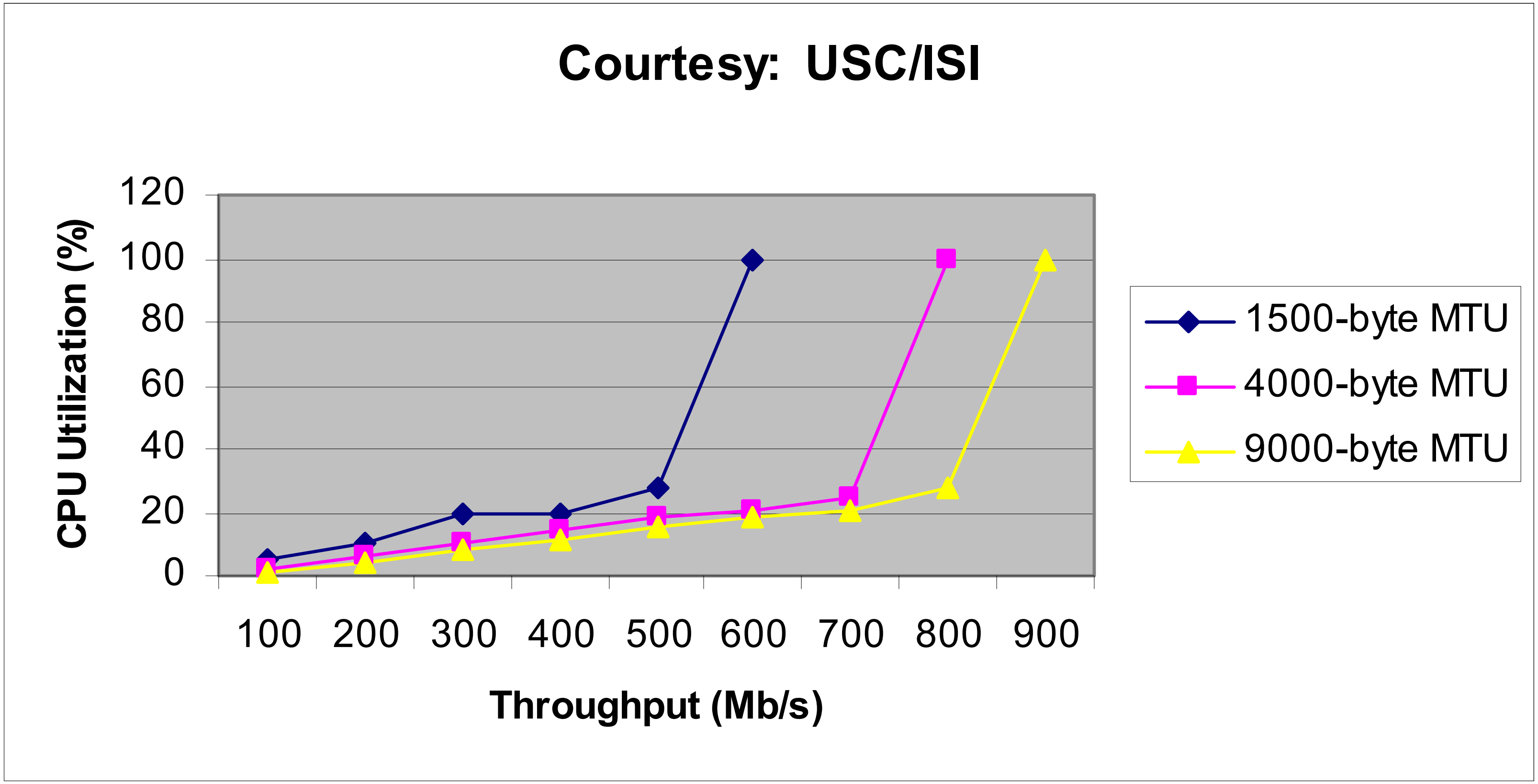
- Host-Interface Bottleneck
  - Software
    - Host can only send & receive packets as fast as the OS can process them.
      - Excessive copying.
      - Excessive CPU utilization.
  - [Hardware (PC) *Not anything wrong with TCP per se.*
    - PCI I/O bus. 64 bit, 66 MHz = 4.2 Gb/s. Solution: InfiniBand?]
- Adaptation Bottlenecks
  - Flow Control
    - No adaptation currently being done in any standard TCP.
    - Static-sized window/buffer is supposed to work for both the LAN & WAN.
  - Congestion Control
    - Adaptation mechanisms will *not* scale, particularly TCP Reno.
    - Adaptation mechanisms *induce* burstiness to the aggregate traffic stream.

Host-Interface Bottleneck (Software)

- First-Order Approximation
  - deliverable bandwidth = maximum-sized packet / interrupt latency
  - e.g., 1500-byte MTU / 50 μs = 30 MB/s = 240 Mb/s   625 Mb/s – 900+ Mb/s
    CC   no CC
- Problems
  - Maximum-sized packet (or MTU) is only 1500 bytes for Ethernet.
  - Interrupt latency to process a packet is quite high.
  - CPU utilization for network tasks is too high. (See next slide.)
- Solutions Intended to Boost TCP Performance
  - Reduce frequency of interrupts, *e.g., interrupt coalescing or OS-bypass.*
  - Increase effective MTU size, *e.g., interrupt coalescing or jumbograms.*
  - Reduce interrupt latency, *e.g., push checksums into hardware, "zero-copy"*
  - Reduce CPU utilization, *e.g., offload protocol processing to NIC.*

666-MHz Alpha with Linux

(Courtesy: USC/ISI)



Note: The congestion-control mechanism does *not* get “activated” in these tests.

Solutions to Boost TCP Performance

(many non-TCP & non-standard)

- Interrupt Coalescing
  - Increases bandwidth (BW) at the expense of even higher latency.
- Jumbograms
  - Increases BW with minimal increase in latency, but at the expense of more blocking in switches/routers and lack of interoperability.
- ULNI or OS-Bypass Protocol
  - Increases BW & decreases latency by an order of magnitude or more.
  - Integrate OS-bypass into TCP?

    VIA over TCP (IETF Internet Draft, GigaNet, July 2000).
- Interrupt Latency Reduction (possible remedy for TCP)
  - Provide "zero-copy" TCP (*a la* OS-bypass) but OS still middleman.
  - Push protocol processing into hardware, e.g., checksums.

- *Which ones will guide the design of a HP-TCP?*

Benchmarks: TCP

- TCP over Gigabit Ethernet (via loopback interface)
  - Theoretical Upper-Bound: 750 Mb/s due to the nature of TCP Reno.
  - Environment: Red Hat Linux 6.2 OS on 400-MHz & 733-MHz Intel PCs; Alteon AceNIC GigE cards; 32-bit, 33-MHz PCI bus.
  - Test: Latency & bandwidth over loopback interface.
    - Latency: O(50 μs).
    - Peak BW w/ default set-up: 335 Mb/s (400) & 420 Mb/s (733).
    - Peak BW w/ *manual* tweaks by network gurus at both ends: 625 Mb/s.
      - Change default send/receive buffer size from 64 KB to 512 KB.
      - Enable interrupt coalescing. (2 packets per interrupt.)
      - Jumbograms. *Theor. BW: 18000 / 50 = 360 MB/s = 2880 Mb/s.*
  - Problem: OS is the middleman. Faster CPUs provide slightly less latency and slightly more BW. 10GigE BW for a high-speed connection wasted.

Solution: ULNI?

Problem?
• Congestion control
• Data copies

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Adaptation Bottleneck

- Flow Control
  - Issues
    - No adaptation currently being done in any standard TCP.
    - 32-KB static-sized window/buffer that is supposed to work for both the LAN and WAN.
  - Problem: Large bandwidth-delay products require flow-control windows as large as 1024-KB to fill the network pipe.
  - Consequence: As little as 3% of network pipe is filled.
  - Solutions
    - *Manual* tuning of buffers at send and receive end-hosts.
      - Too small → low bandwidth. Too large → waste memory (LAN).
    - *Automatic* tuning of buffers.
      - PSC: Auto-tuning but does not abide by TCP semantics, 1998.
      - LANL: Dynamic flow control, 2000. Increase BW by 8 times. Fair?
    - *Network striping & pipelining* with default buffers. Unfair. UIC, 2000.

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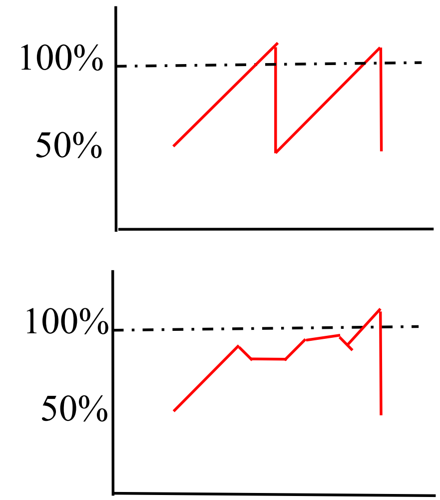
Adaptation Bottleneck

- Congestion Control
  - Adaptation mechanisms will *not* scale due to
    - Additive increase / multiplicative decrease algorithm (see next slide).
      - *Induces* bursty (i.e., self-similar or fractal) traffic.
  - TCP Reno congestion control
    - Bad: Allow/induce congestion.
      Detect & recover from congestion.

      Analogy: "Deadlock detection & recovery" in OS.
    - Result: "At best" 75% utilization in steady state.
  - TCP Vegas congestion control
    - Better: Approach congestion but try to *avoid* it.
      Usually results in better network utilization.

      Analogy: "Deadlock avoidance" in OS.

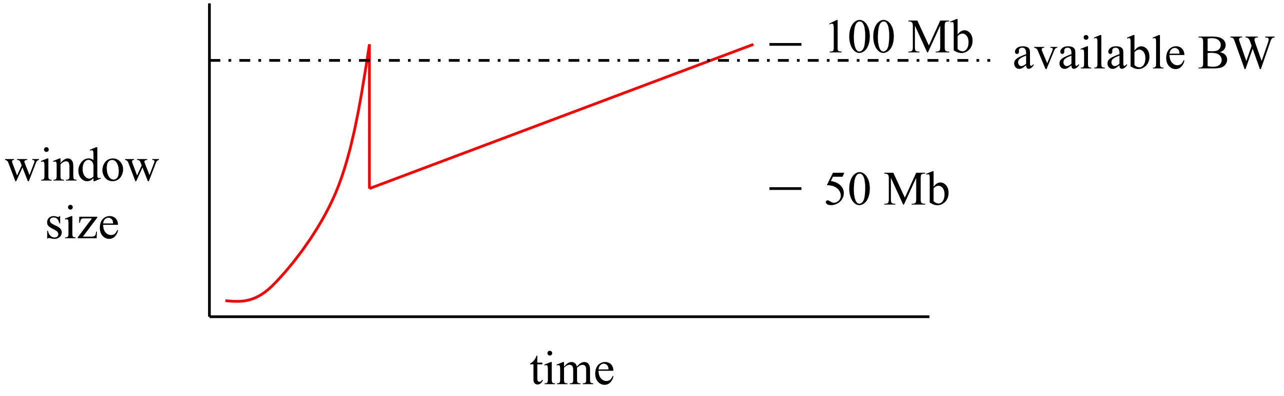
Utilization vs. Time



"Optimal" Bandwidth

- The future performance of computational grids (as well as clusters & supercomputers trying to get away from ULNI scalability problems) looks bad if we continue to rely on the widely-deployed TCP Reno.

  Example: High BW-delay product: 1 Gb/s WAN * 100 ms RTT = 100 Mb
- Additive increase
  - when window size is 1 ⟶ 100% increase in window size.
  - when window size is 1000 ⟶ 0.1% increase in window size.



Re-convergence to "optimal" bandwidth takes nearly 7 minutes! (Performance is awful if network uncongested.)

AIMD Congestion Control

- Stable & fair (under certain assumptions of synchronized feedback) but
  - ➢ Not well-suited for emerging applications (e.g., streaming & real-time audio and video)
    - Its reliability and ordering semantics increases end-to-end delays and delay variations.
    - Multimedia applications *generally* do not react well to the large and abrupt reductions in transmission rate caused by AIMD.
  - ➢ Solutions
    - Deploy "TCP-friendly" (non-AIMD) congestion-control algorithms, e.g., binomial congestion-control algorithms such as inverse increase / additive decrease (MIT).
    - Provide a protocol that functionally "sits" between UDP & TCP, e.g., RAPID: Rate-Adjusting Protocol for Internet Delivery
      - n% reliability (vs. 100% reliability of TCP) where $0\% < n \leq 100\%$
      - Provide high performance *and* utilization regardless of network conditions.
      - Hmm … what about wireless?

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How to Build a HP-TCP?

- Host-Interface Bottleneck
  - Software
    - A host can only send and receive packets as fast as the OS can process the packets.
  - Hardware (PC)
    - PCI I/O bus. 64 bit, 66 MHz = 4.2 Gb/s. Solution: InfiniBand?

BW problems potentially solvable. Latency?
What happens when we go optical to the chip?

Based on past trends, the I/O bus will continue to be a bottleneck.

- Adaptation Bottlenecks
  - Flow Control
    - No adaptation currently being done in any standard TCP.
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    - Adaptation mechanisms will *not* scale, particularly TCP Reno.

Solutions exist but are not widely deployed.

TCP Vegas? Binomial congestion control?

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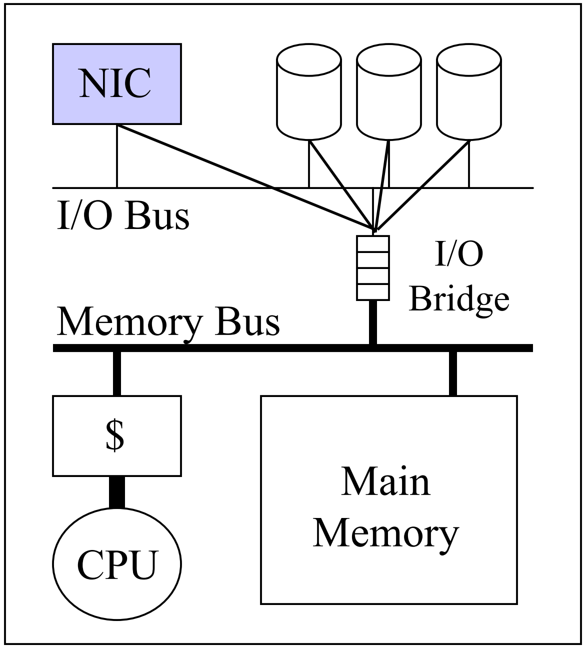
Crossroads for High-Performance Networking

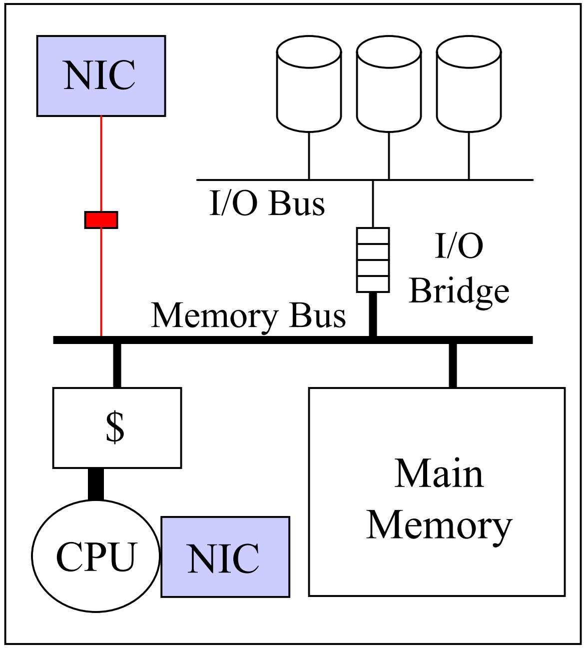
http://www.canet3.net/library/papers/wavedisk.doc

- Hardware/Architecture
  - ➢ InfiniBand helps but network-peer CPU (or co-processor) or network-integrated microprocessor architecture may be needed.

Today



Near Future



Far Future: Network is Storage
Memory- & disk-access too slow.

Software Bottleneck?
Offload as much protocol processing to the NIC CPU

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Crossroads for High-Performance Networking

Software

	Internet Community		*HPC Community*
Early 1990s		TCP Tahoe/Reno	
Mid-1990s	TCP Tahoe/Reno		specialized ULNI
Late 1990s	TCP Tahoe/Reno	TCP Vegas	standardized ULNI
Tomorrow	TCP Tahoe/Reno	"TCP Vegas"	standardized ULNI (extend to WAN, e.g., add IP routing, congestion control, MTU discovery)

SANs

grids

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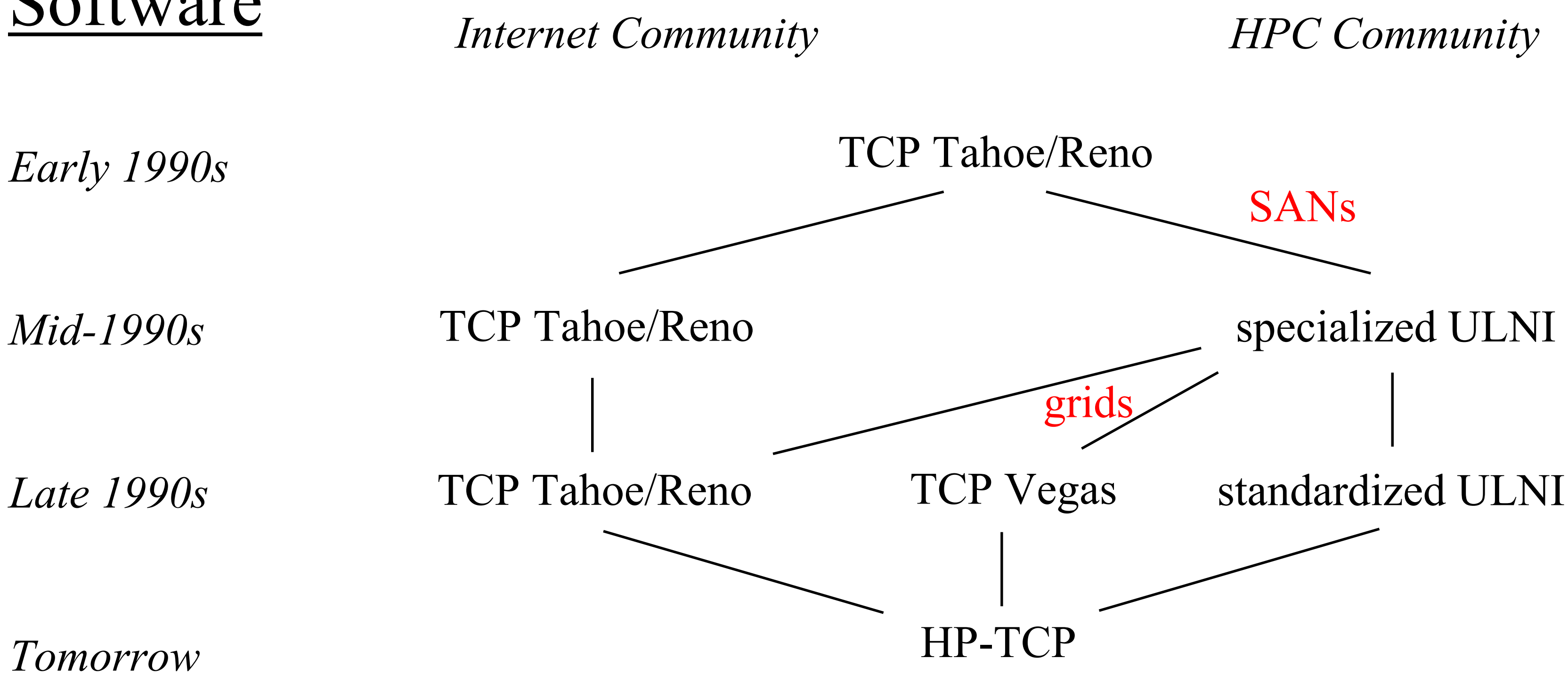
Crossroads for High-Performance Networking

Software



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That’s all folks!