Introduction to Multithreading and Multiprocessing in the FreeBSD SMPng Network Stack

EuroBSDCon 2005
26 November 2005

Robert Watson
FreeBSD Core Team
rwatson@FreeBSD.org

Computer Laboratory
University of Cambridge

Ed Maste
FreeBSD Developer
emaste@FreeBSD.org

Sandvine, Inc.

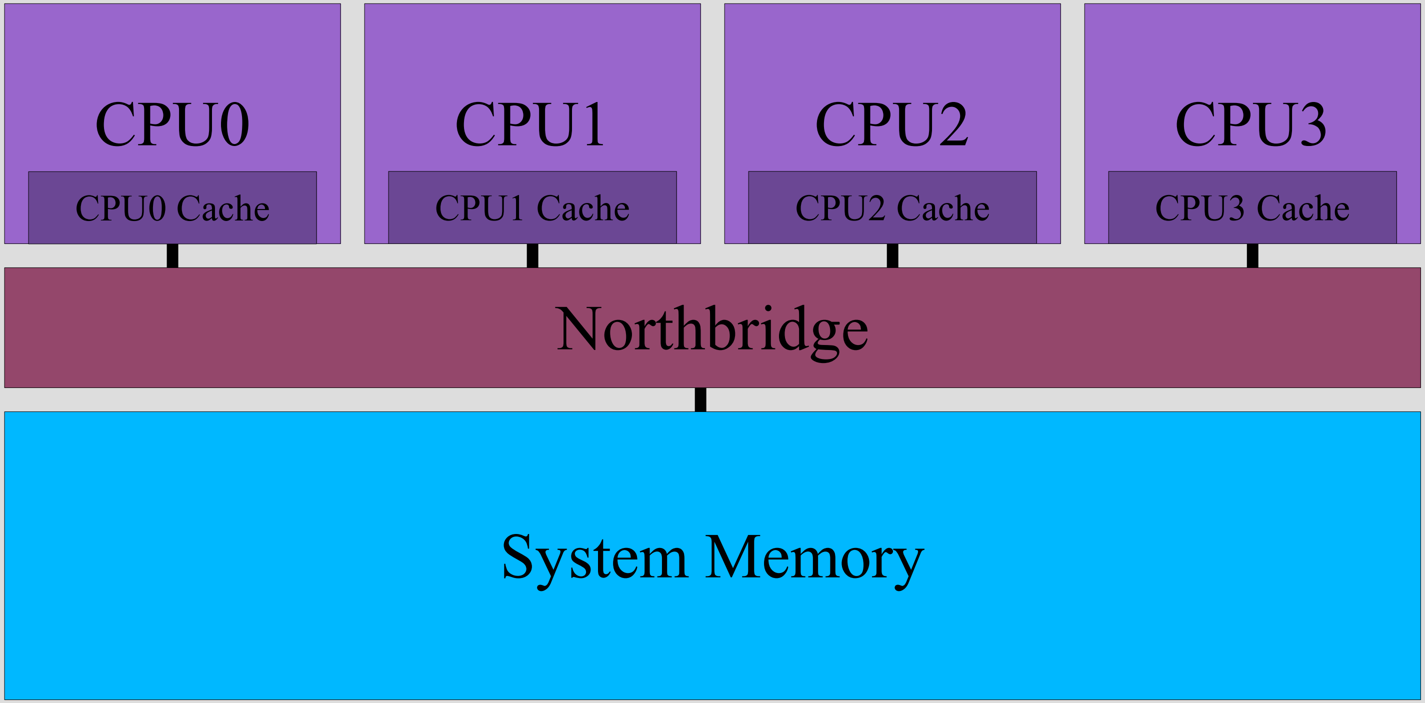
Introduction

- Background
  - Symmetric Multi-Processing (SMP)
  - Strategies for SMP-capable operating systems
- SMPng Architecture
  - FreeBSD 3.x/4.x SMP
  - FreeBSD 5.x/6.x SMPng
- Network Stack
  - Architecture
  - Synchronization approaches
  - Optimization approaches

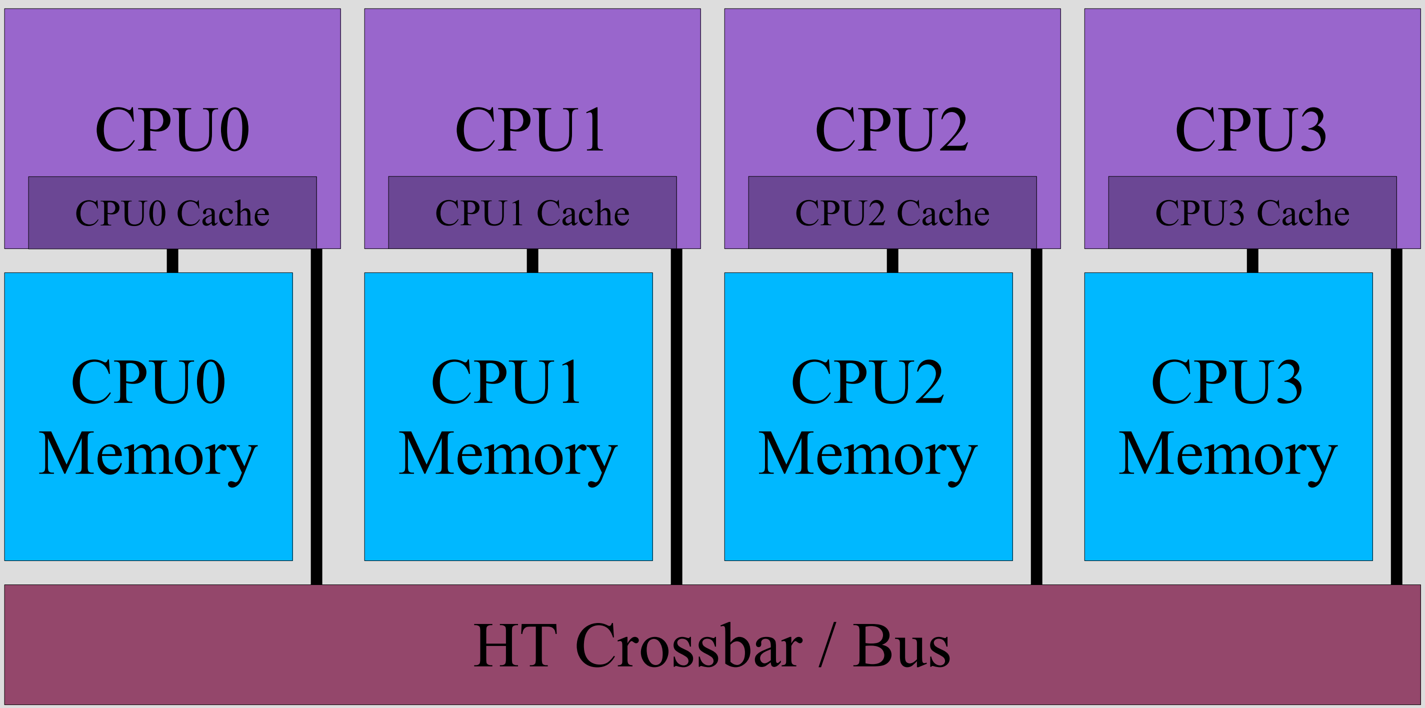
Multi-Processing (MP) and Symmetric Multi-Processing (SMP)

- Symmetric Multi-Processing (SMP)
  - More than one general purpose processor
  - Running the same primary system OS
  - Increase available CPU capacity sharing memory/IO resources
- “Symmetric”
  - Refers to memory performance and caching
  - In contrast to NUMA
    - Non-Uniform Memory Access
  - In practice, a bit of both
    - Amd64 NUMA, dual core, etc.
    - Intel HTT, dual core, etc.

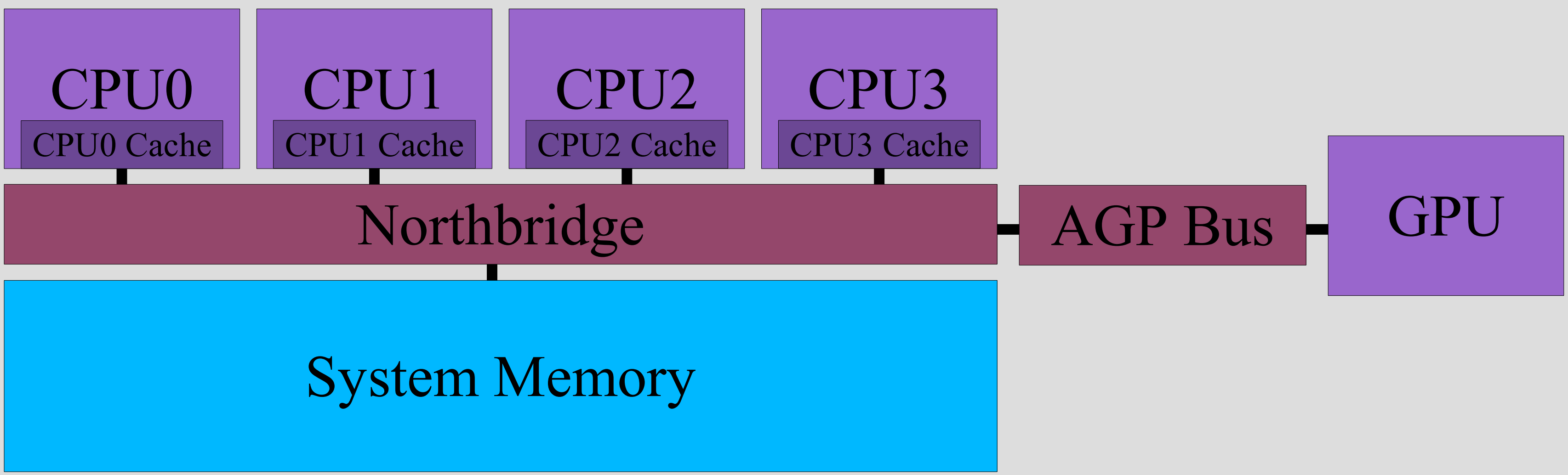
Simplified SMP Diagram Intel Quad Xeon



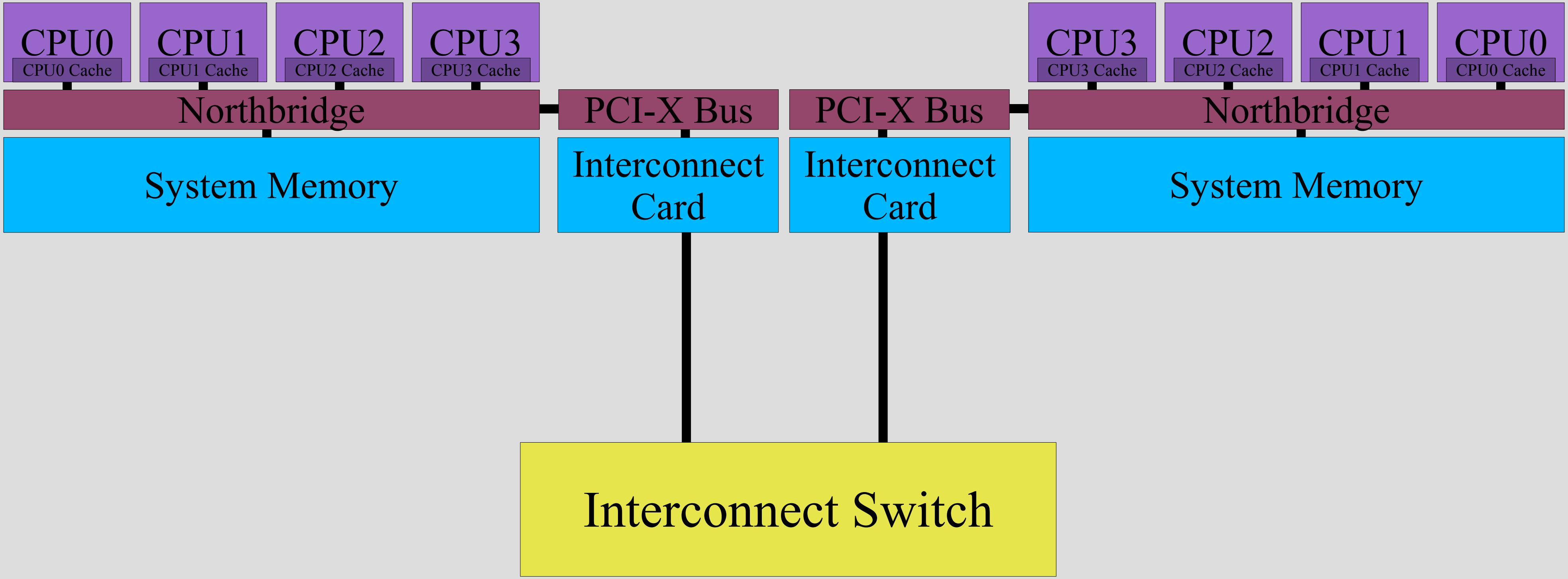
Simplified NUMA Diagram
Quad AMD Opteron



Not SMPng: Graphics Processing Units (GPUs)



Not SMPng: Loosely Connected Computation Clusters



What is shared in an SMP System?

Shared	Not Shared
System memory PCI buses I/O channels ...	CPU (register context, TLB, ...) Cache Local APIC timer ...

- Sources of asymmetry
  - Hyper-threading (HTT): physical CPU cores share computation resources and caches
  - Non-Uniform Memory Access (NUMA): different CPUs may access regions of memory at different speeds

What is an MP-Capable OS?

- An OS is MP-capable if it is able to operate correctly on MP systems
  - This could mean a lot of different things
  - Usually implies it is able to utilize >1 CPU
- Common approach is Single System Image
  - “Look like a single-processor system”
  - But be faster
- Other models are possible
  - Most carefully select variables to degrade
  - Weak memory models, message passing, ...

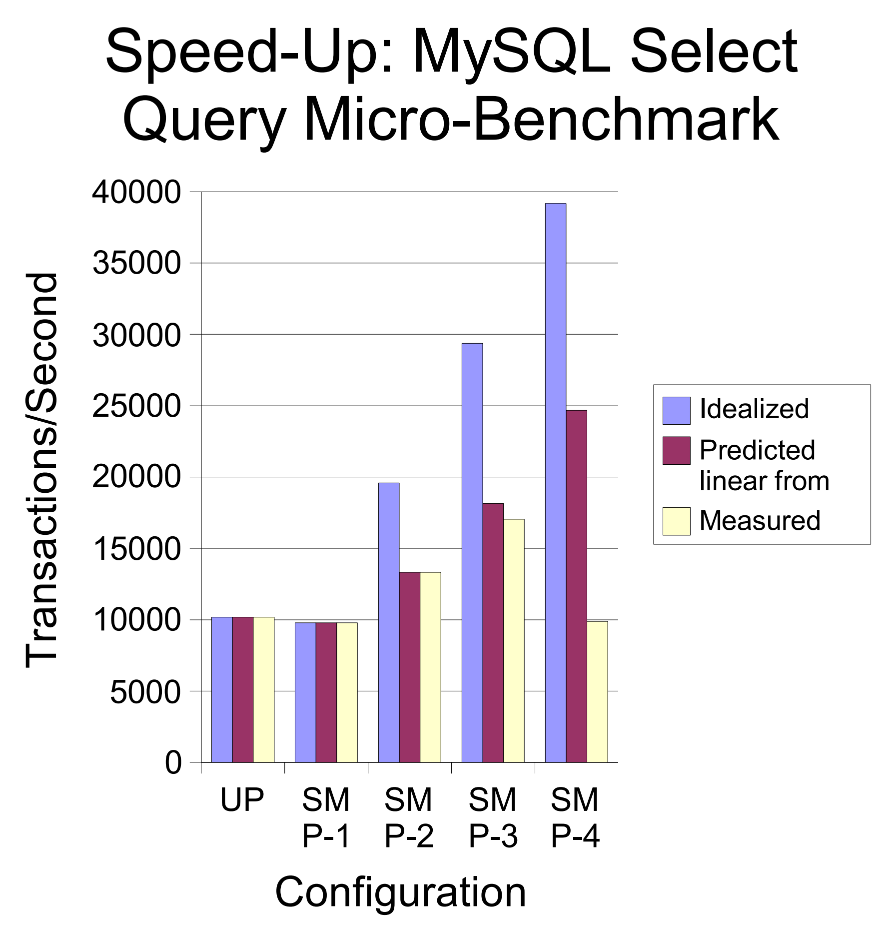
OS Approach: Single System Image (SSI)

- To the extent possible, maintain the appearance of a single-processor system
  - Only with more CPU power
- Maintain current UNIX process model
  - Parallelism between processes
  - Parallelism in thread-enabled processes
  - Requires minimal changes to applications yet offer significant performance benefit
- Because the APIs and services weren't designed for MP, not always straight forward

Definition of Success

- Goal is performance
  - Why else buy more CPUs?
  - However, performance is a nebulous concept
    - Very specific to workload
  - Systems programming is rife with trade-offs
- “Speed up”
  - Measurement of workload performance as number of CPUs increase
  - Ratio of score on N processors to score on 1
- Two goals for the OS
  - Don't get in the way of application speed-up
  - Facilitate application speed-up

“Speed-Up”



- “Idealized” performance
- Not realistic
  - OS + application synchronization overhead
  - Limits on workload parallelism
  - Contention on shared resources, such as I/O + bus

Developing an SMP UNIX System

- Two easy steps
  - Make it run
  - Make it run fast
- Well, maybe a little more complicated
  - Start with the kernel
  - Then work on the applications
  - Then repeat until done

Issues relating to MP for UNIX Operating Systems: Kernel

- Bootstrapping
- Inter-processor communication
- Expression of parallelism
- Data structure consistency
- Programming models
- Resource management
- Scheduling work
- Performance

Issues relating to MP for UNIX Operating Systems: Apps

- Application must be able use parallelism
  - OS must provide primitives to support parallel execution
    - Processes, threads
  - OS may do little, some, or lots of the work
    - Network stack
    - File system
  - An MP-capable and MP-optimized thread library is very important
- System libraries and services may need a lot of work to work well with threads

Inter-Processor Communication

- Inter-Processor Interrupts (IPI)
  - Wake up processor at boot time
  - Cause a processor to enter an interrupt handler
  - Comes with challenges, such as deadlocks
- Shared Memory
  - Kernel memory will generally be mapped identically when the kernel executes on processors
  - Memory is therefore shared, and can be read or written from any processor
  - Requires consistency and synchronization model
  - Atomic operations, higher level primitives, etc.

Expression of Parallelism

- Kernel will run on multiple processors
  - Most kernels have a notion of threads similar to user application threads
  - Multiple execution contexts in a single kernel address space
  - Threads will execute on only one CPU at a time
  - All execution in a thread is serialized with respect to itself
  - Most systems support migration of threads between processors
  - When to migrate is a design choice affecting load balancing and synchronization

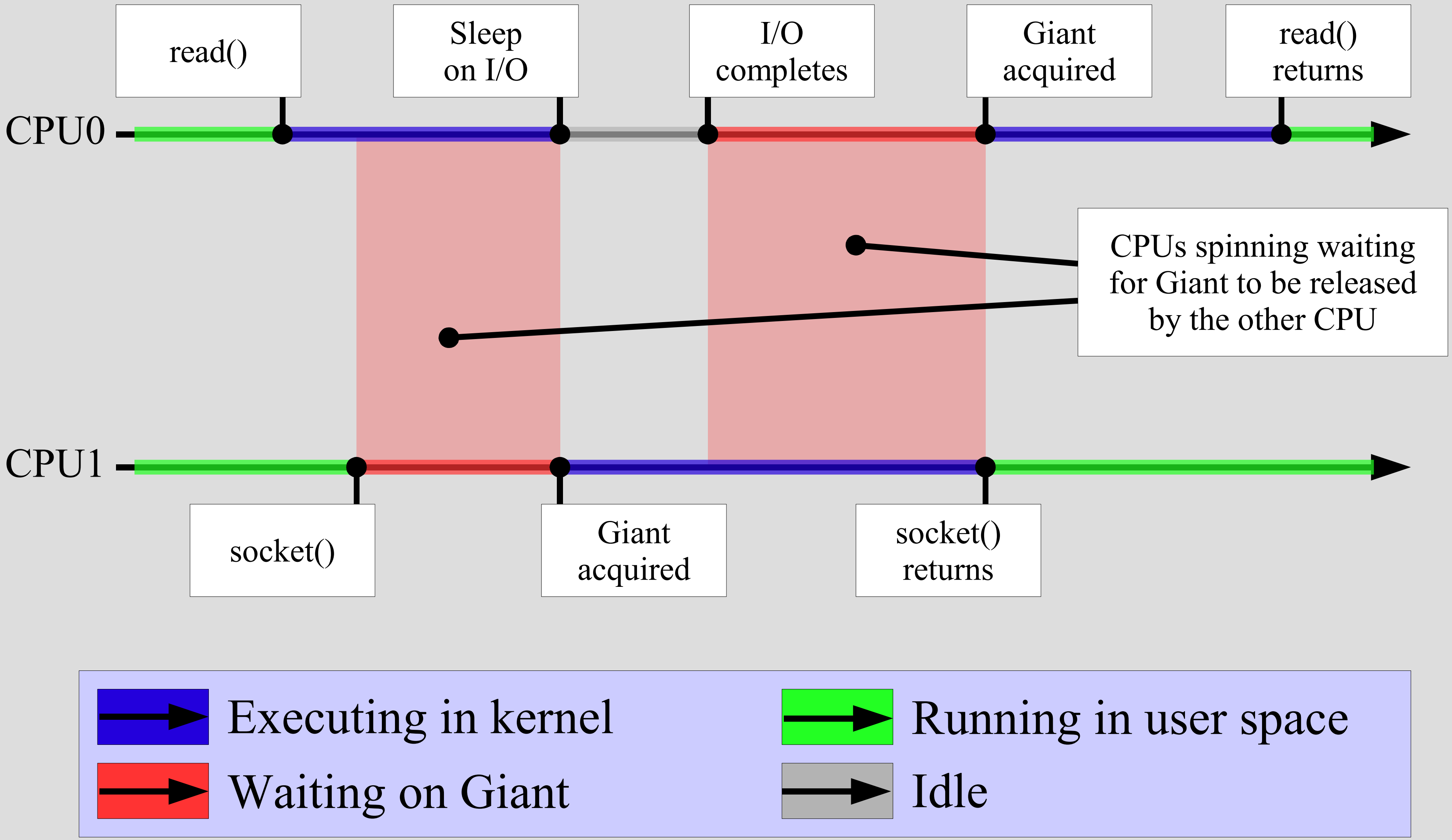
Data Consistency

- Some kernel data structures will be accessed from more than one thread at a time
  - Will become corrupted unless access is synchronized
  - “Race Conditions”
- Low level primitives are usually mapped into higher level programming services
  - From atomic operations and IPIs
  - To mutexes, semaphores, signals, locks, ...
  - Lockless queues and other lockless structures
- Choice of model is very important
  - Affects performance and complexity

Data Consistency: Giant Lock Kernels

- Giant Lock Kernels (FreeBSD 3.x, 4.x)
  - Most straight forward approach to MP OS
  - User process and thread paralellism
  - Kernel executes on one processor at a time to maintain kernel programming invariants
    - Only one can enter the kernel at a time
    - Processors spin if waiting for the kernel
- Easy to implement, but lots of “contention”
  - No in-kernel parallelism

Context Switching in a Giant-Locked Kernel



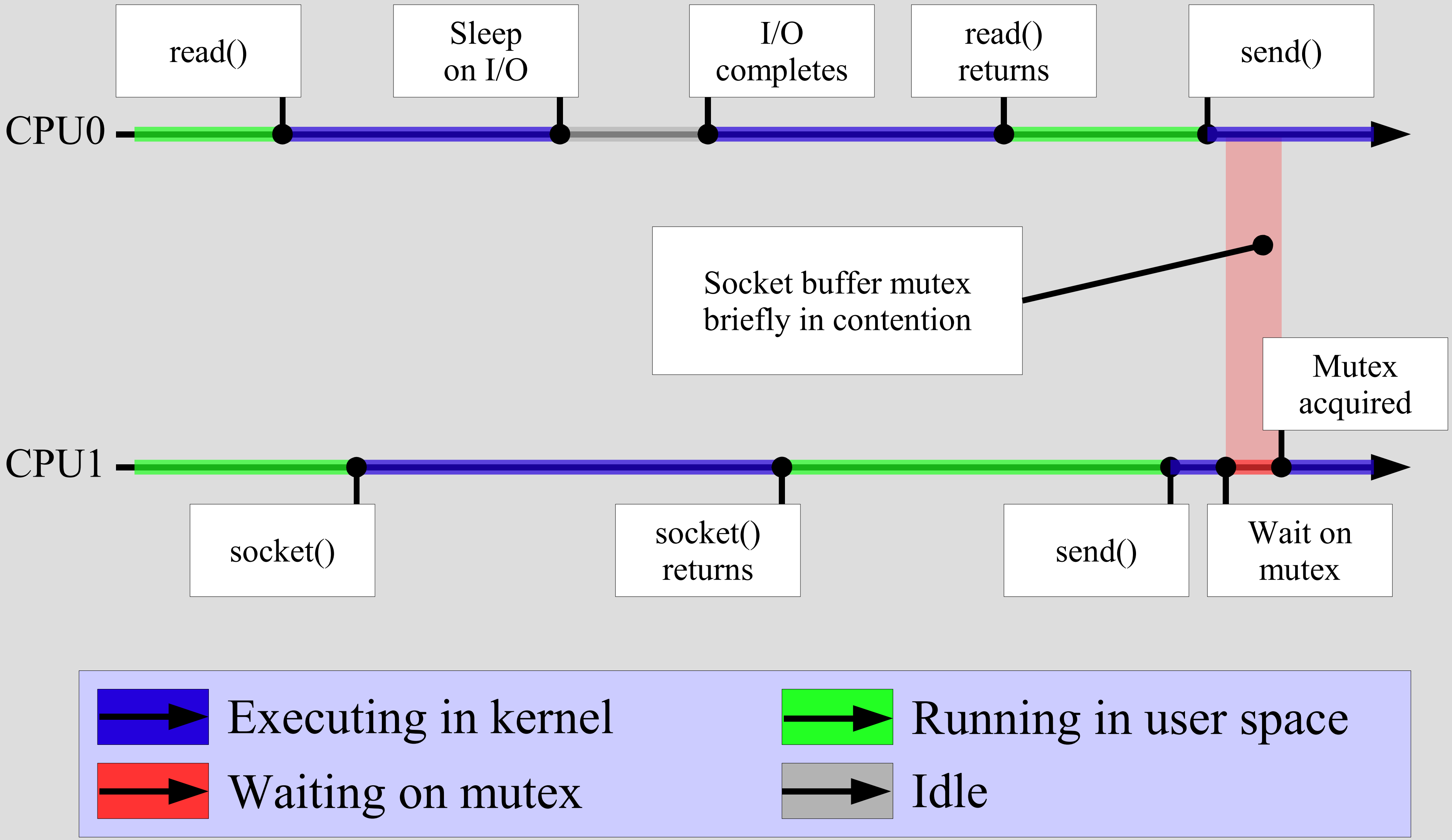
The Problem: Giant Contention

- Contention in a Giant lock kernel occurs when tasks on multiple CPUs compete to enter the kernel
  - User threads performing system calls
  - Interrupt or timer driver kernel activity
- Occurs for workloads using kernel services
  - File system activity
  - Network activity
  - Misc. I/O activity
  - Inter-Process Communication (IPC)
  - Scheduler and context switches
- Also affects UP by limiting preemption

Addressing Contention: Fine-Grained Locking

- Decompose the Giant lock into a series of smaller locks that contend less
  - Typically over “code” or “data”
  - E.g., scheduler lock permits user context switching without waiting on the file system
  - Details vary greatly by OS
- Iterative approach
  - Typically begin with scheduler lock
  - Dependency locking such as memory allocation
  - Some high level subsystem locks
  - Then data-based locking
  - Drive granularity based on observed contention

Context Switching in a Finely Locked Kernel



FreeBSD SMPng Project

- SMPng work began in 2001
  - Present in FreeBSD 5.x, 6.x
- Several architectural goals
  - Adopt more threaded architecture
    - Threads represent possible kernel parallelism
    - Permit interrupts to execute as threads
  - Introduce various synchronization primitives
    - Mutexes, SX locks, rw locks, semaphores, CV's
  - Iteratively lock subsystems and slide Giant off
- Start with common dependencies
  - Synchronization, scheduling, memory allocation, timer events, ...

FreeBSD Kernel

- Several million lines of code
- Many complex subsystems
  - Memory allocation, VM, VFS, network stack, System V IPC, POSIX IPC, ...
- FreeBSD 5.x
  - Most major subsystems except VFS and some drivers execute Giant-free
  - Some network protocols require Giant
- FreeBSD 6.x almost completely Giant-free
  - VFS also executes Giant-free, although some file systems are not
  - Some straggling device drivers require Giant

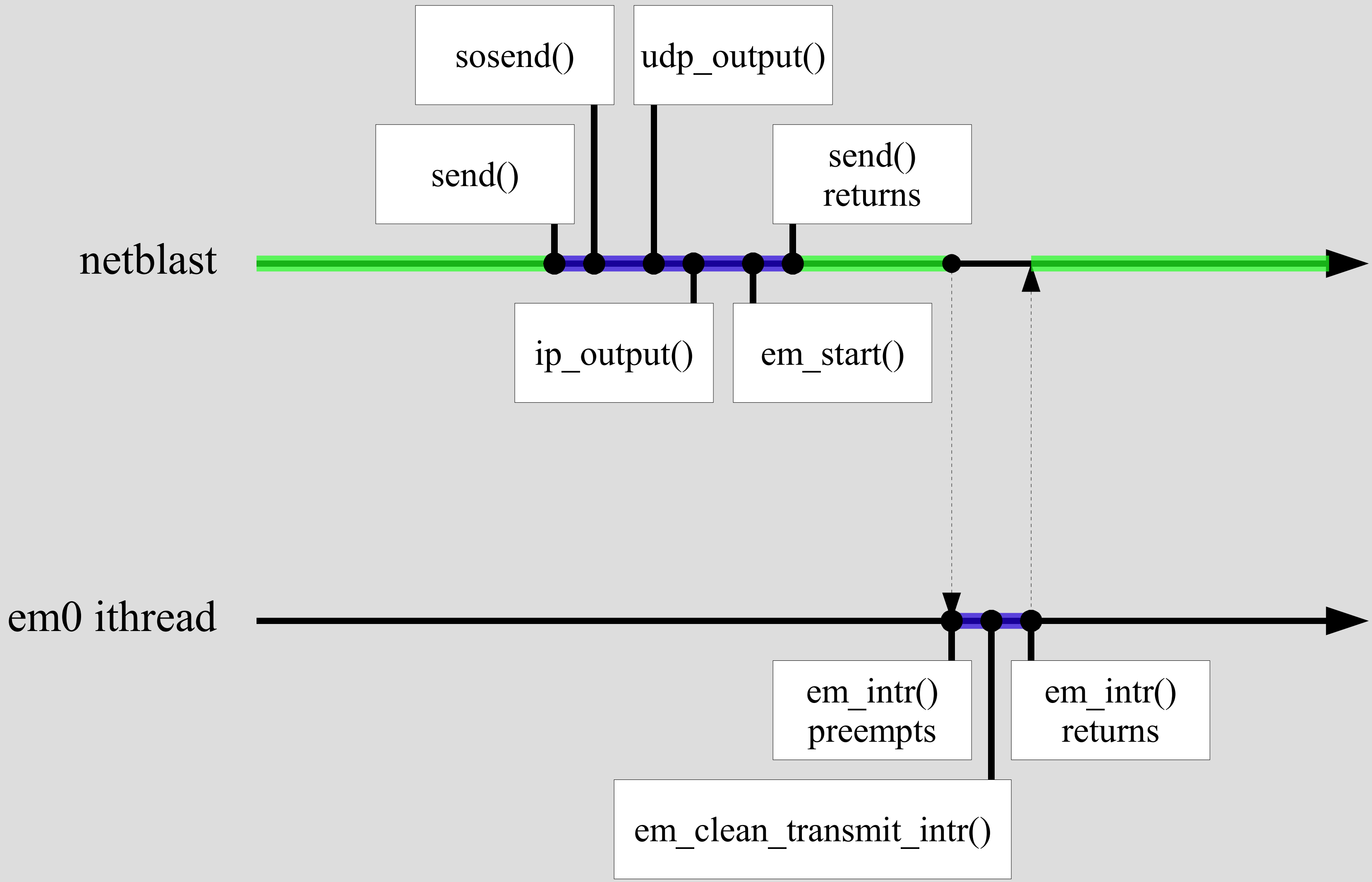
Network Stack Components

- Over 400,000 lines of code
  - Excludes distributed file systems
  - Excluding device drivers
- Several significant components
  - “mbuf” memory allocator
  - Network device drivers, interface abstraction
  - Protocol-independent routing and event model
  - Link-layer protocols, network-layer protocols
    - Includes IPv4, IPv6, IPSEC, IPX, EtherTalk, ATM
  - Sockets and socket buffers
  - Netgraph extension framework

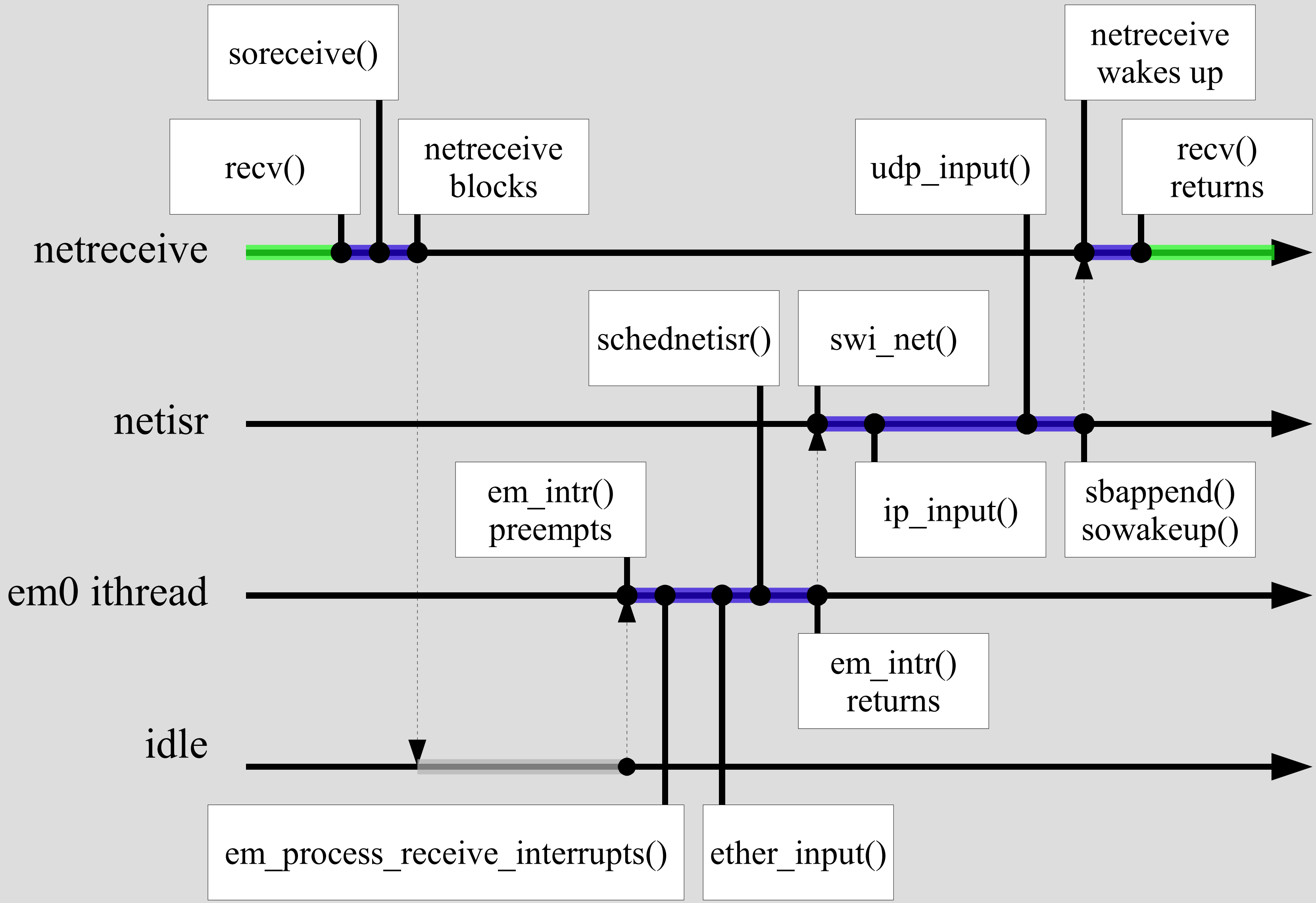
Sample Data Flow
TCP Send and Receive

System call and socket	kern_send()	kern_recv()
	sosend() sbappend()	soreceive() sbappend()
TCP	tcp_send() tcp_output()	tcp_reass() tcp_input()
IP	ip_output()	ip_input()
Link Layer, Device Driver	ether_output()	ether_input()
	em_start()	em_intr()

Network Stack Threading
UDP Transmit



Network Stack Threading UDP Receive



Network Stack Concerns

- Overhead: Per-packet costs
  - Network stacks may process millions of PPS
  - Small costs add up quickly if per-packet
- Ordering
  - TCP is very sensitive to mis-ordering
- Optimizations may conflict
  - Optimizing for latency may damage throughput, and vice versa
- When using locks, ordering is important
  - Lock orders prevent deadlock
  - Data passes in various directions through layers

Locking Strategy

- Lock data structures
  - Don't use finer locks than required by UNIX API
    - I.e., parallel send and receive on the same socket is useful, but not parallel send on the same socket
  - Lock references to in-flight packets, not packets
  - Layers have their own locks as objects at different layers have different requirements
- Lock orders
  - Driver locks are leaf locks with respect to stack
  - Protocol drives most inter-layer activity
  - Acquire protocol locks before driver locks
  - Acquire protocol locks before socket locks
  - Avoid lock order issues via deferred dispatch

Network Stack Parallelism

- Network stack was already threaded in 4.x
  - 4.x had user threads, netisr, dispatched crypto
  - 5.x/6.x add ithreads
- Assignment of work to threads
  - Threads involved are typically user threads, netisr, and ithreads
  - Work split over many threads for receive
  - On transmit, work tends to occur in one thread
  - Opportunities for parallelism in receive are greater than in transmit for a single user thread

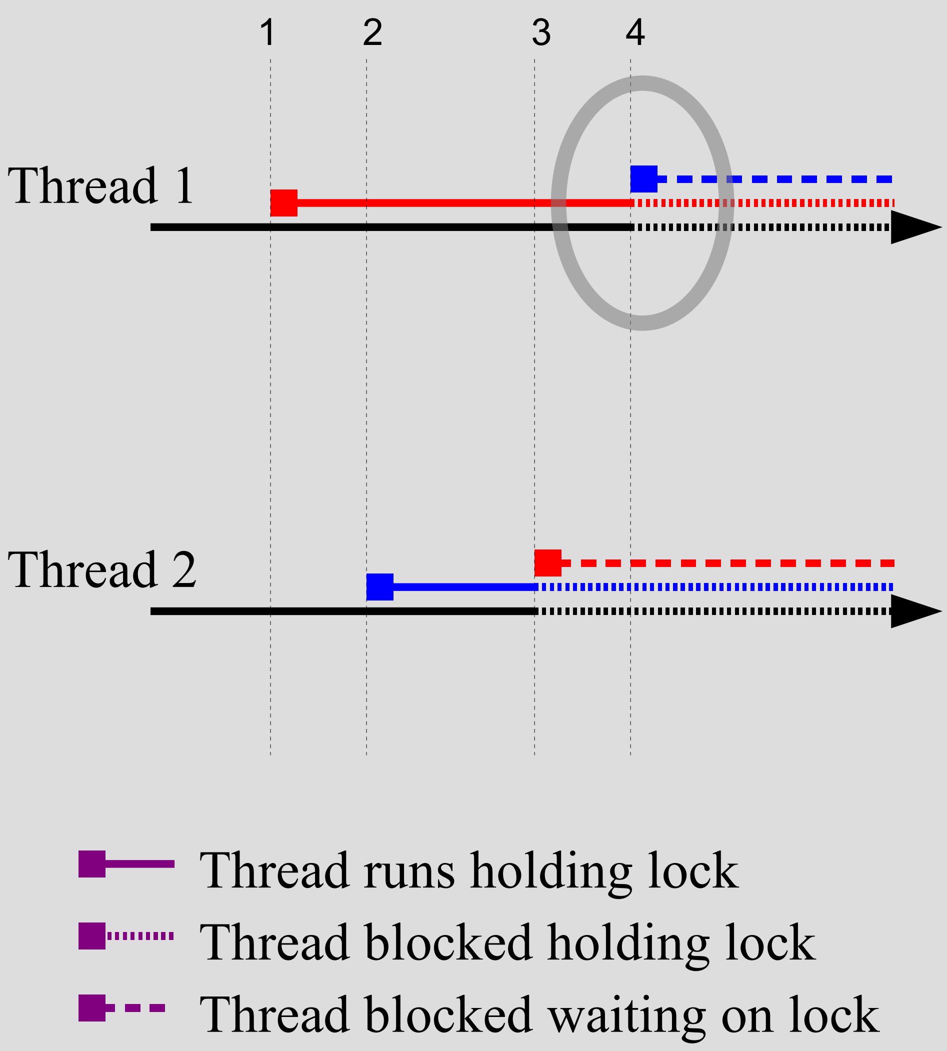
Approach to Increasing Parallelism

- Starting point
  - Assume a Giant-free network stack
  - Select an interesting workload
  - What are remaining source of contention?
  - Where is CPU-intensive activity serialized in a single thread – leading to unbalanced CPU use?
- Identify natural boundaries in processing
  - Protocol hand-offs, layer hand-offs, etc
  - Carefully consider ordering considerations
- Weigh trade-offs, look for amortization
  - Context switches are expensive
  - Locks are expensive

MP Programming Challenges

- MP programming is rife with challenges
- A few really important ones
  - Deadlock
  - Locking Overhead
  - Event Serialization

Challenge: Deadlock

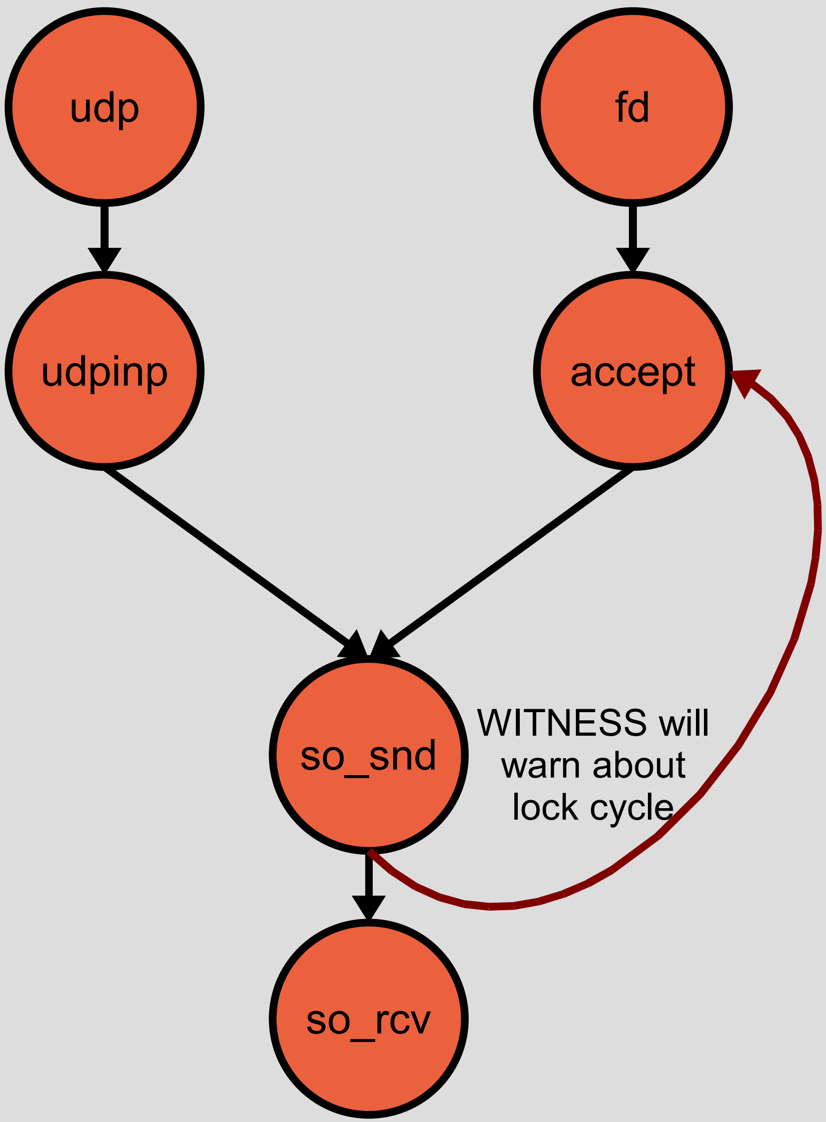


- "Deadly Embrace"
- Classic deadlocks
  - Lock cycles
  - Any finite resource
- Classic solutions
  - Avoidance
  - Detect + recover
- Avoid live locks!

Deadlock Avoidance in FreeBSD SMPng

- Hard lock order
  - Applies to most mutexes and sx locks
  - Disallow lock cycles
  - WITNESS lock verification tool
- Variable hierarchal lock order
  - Lock order a property of data structures
  - At any given moment, the lock order is defined
  - However, it may change as data structure changes
- Master locks
  - Master lock used to serialize simultaenous access to multiple leaf locks

Lock Order Verification: WITNESS

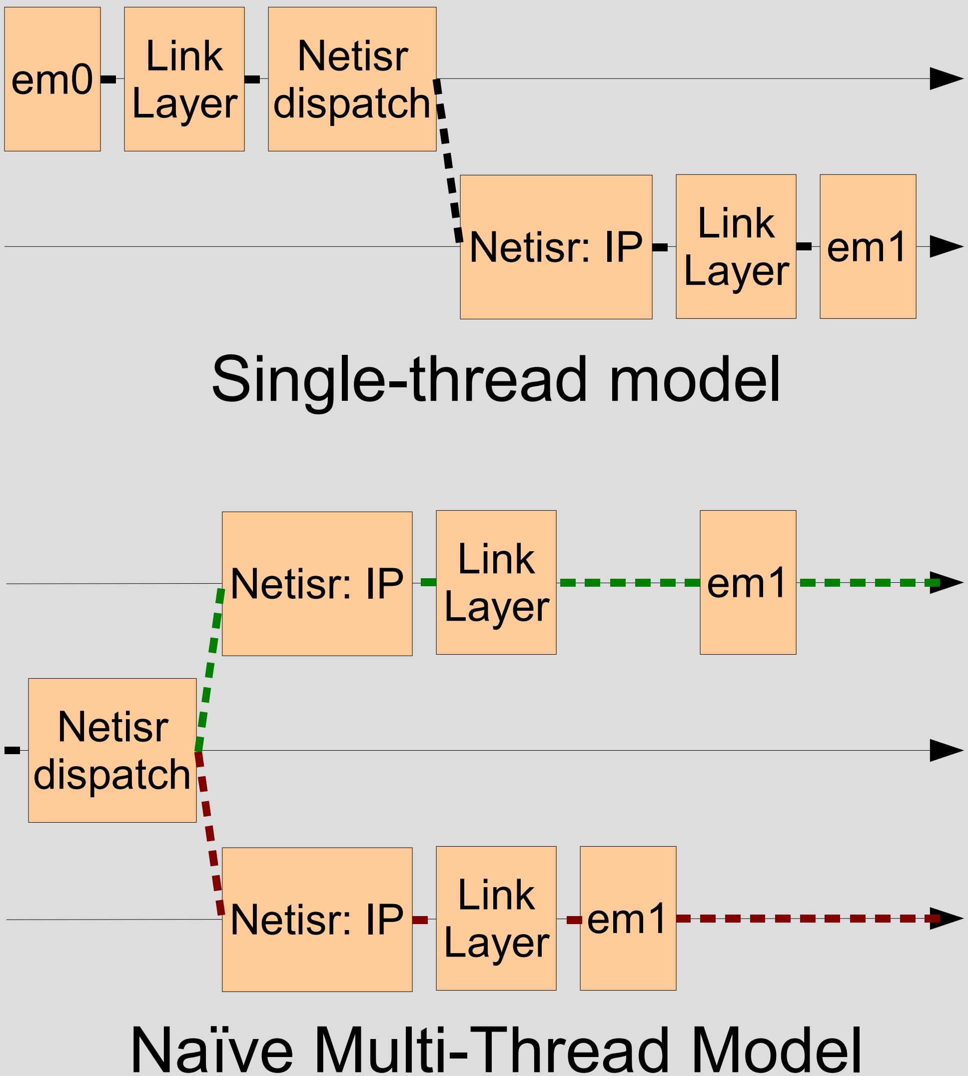


- Run-time lock order monitor
  - Tracks lock acquisitions
  - Builds graph reflecting order
  - Detects and warns about cycles
- Supports both hard-coded and dynamic discovery of order
- Expensive but useful

Mitigating Locking Overhead

- Amortize cost of locking
  - Avoid multiple lock operations where possible
  - Amortize cost of locking over multiple packets
- Coalesce/reduce number of locks
  - Excessive granularity will increase overhead
  - Combining across layers can avoid lock operations necessitated by to lock order
- Serialization “by thread”
  - Execution of threads is serialized
- Serialization “by CPU”
  - Use of per-CPU data structures and pinning/critical sections

Challenge: Event Serialization



- Ordering of packets is critical to performance
  - TCP will misinterpret reordering as requiring fast retransmit
- Ordering constraints must be maintained across dispatch
- Naïve threading violates ordering

Ensuring Sufficient Ordering

- Carefully select an ordering
  - “Source ordering” is used widely in the stack
    - Polling thread(s)
    - Ithread Direct Dispatch
  - Weakening ordering can improve performance
  - Some forms of parallelism maintain ordering more easily than others

Status of SMPng Network Stack

- FreeBSD 5.x and 6.x largely run the network stack without Giant
  - Some less mainstream components still need it
- From "Make it work" to "Make it work fast!"
  - Many workloads show significant improvements: databases, multi-thread/process TCP use, ...
  - Cost of locking hampers per-packet performance for specific workloads: forwarding/bridging PPS
  - UP performance sometimes sub-optimal
  - Of course, 4.x is the gold standard...
- Active work on performance measurement and optimization currently

Summary

- A lightning fast tour of MP
  - Multi-processor system architectures
  - Operating system interactions with MP
  - SMPng architecture and primitives
- And the network stack on MP
  - The FreeBSD network stack
  - Changes made to the network stack to the network stack to allow it to run multi-threaded
  - Optimization concerns including locking cost and increasing parallelism
  - Concerns such as packet ordering

Conclusion

- SMPng is present in FreeBSD 5.x, 6.x
  - 5.3-RELEASE the first release with Giant off the network stack by default; 5.4-RELEASE includes stability, performance improvements.
  - 6.x includes substantial optimizations, MPSAFE VFS
- Some URLs:

  http://www.FreeBSD.org/
  http://www.FreeBSD.org/smp/
  http://www.FreeBSD.org/projects/netperf/
  http://www.watson.org/~robert/freebsd/netperf/