# FreeBSD SMPng Project
# SMP Network Stack


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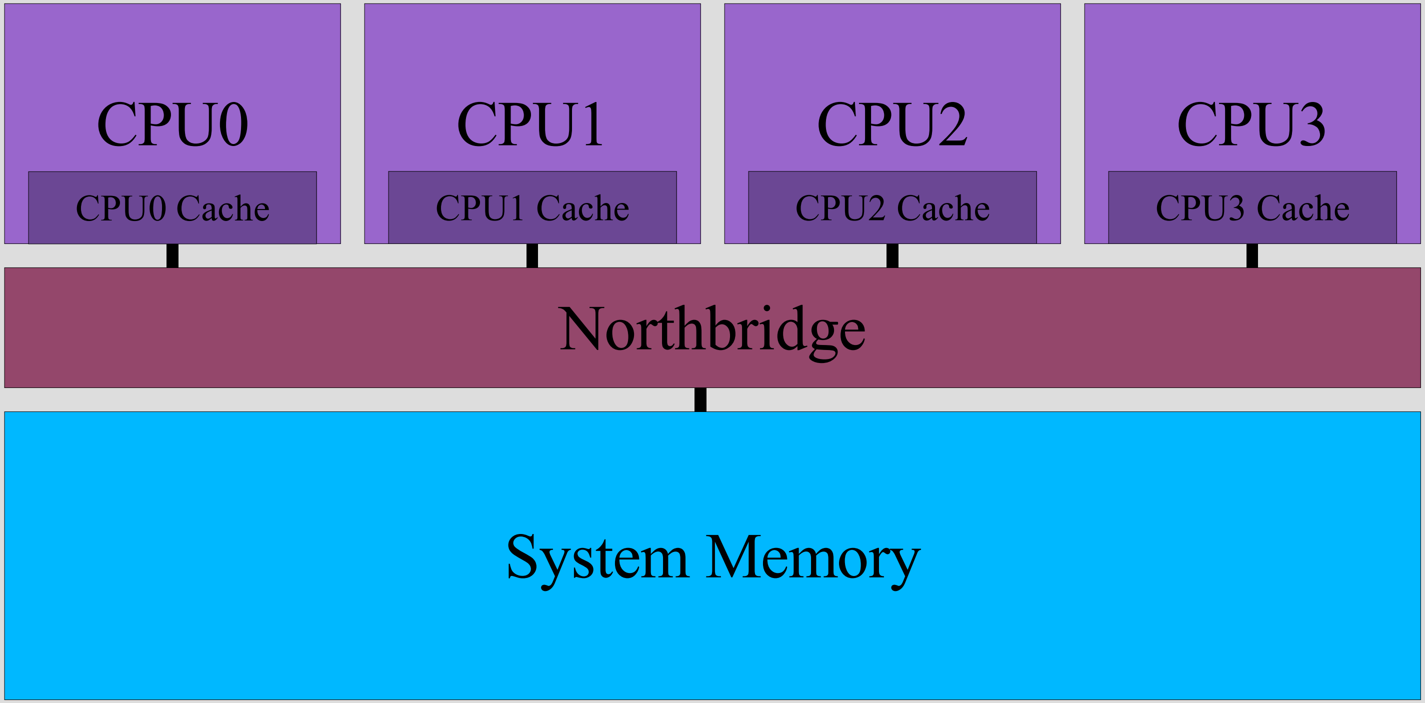
# Introduction

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

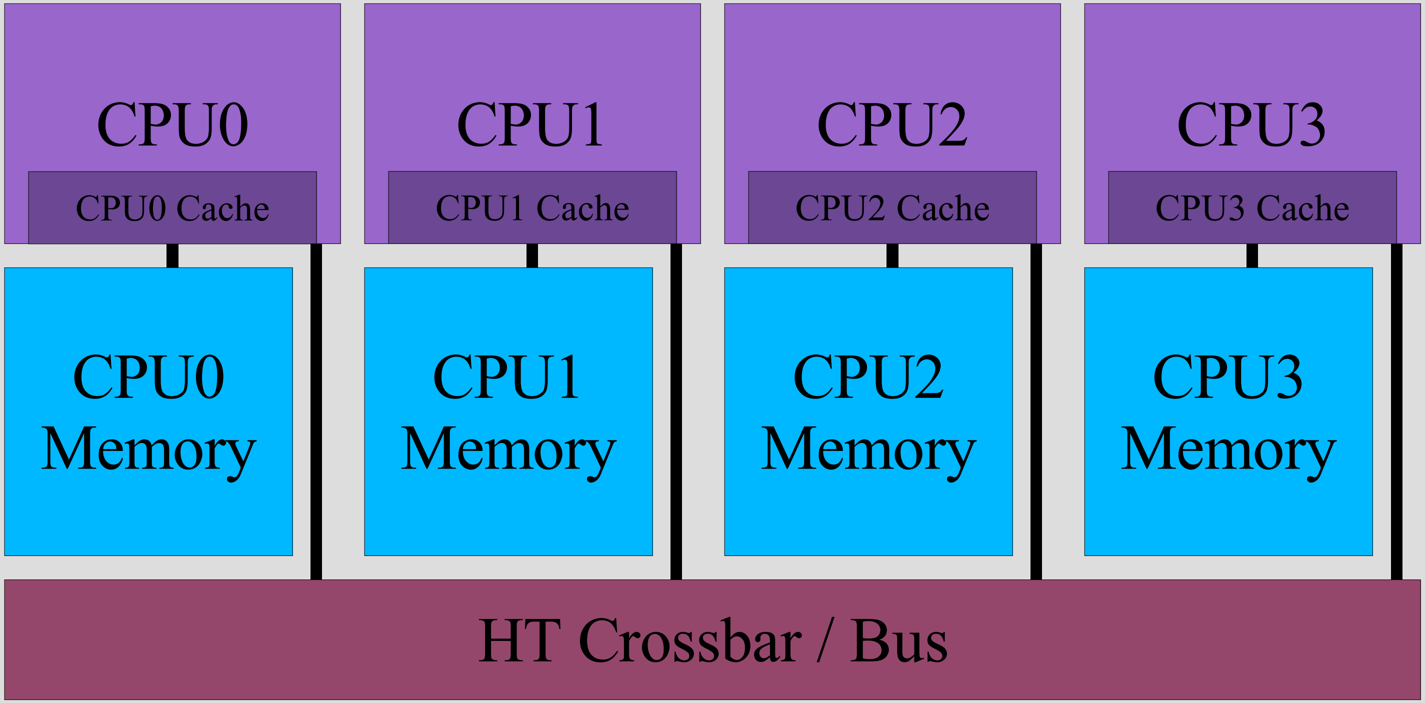
# Multi-Processing (MP) and Symmetric Multi-Processing (SMP)

- Interested in “mostly” 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, the world is complicated
  - Amd64 NUMA, dual core, etc.
  - Intel HTT, dual core, etc.

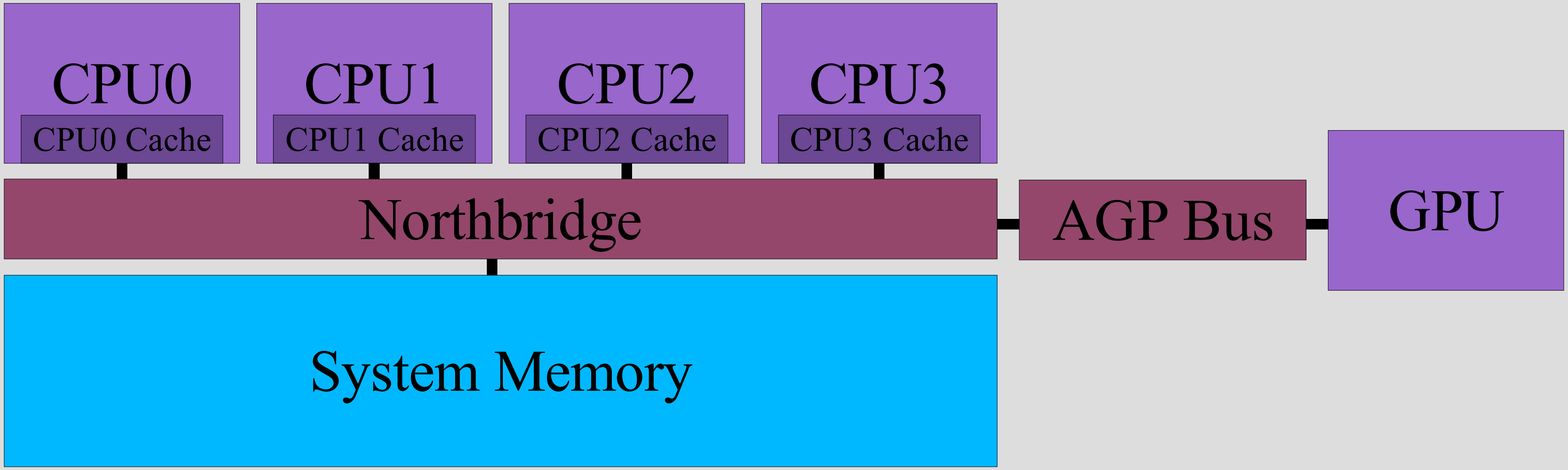
# Simplified SMP Diagram
# Intel Quad Xeon



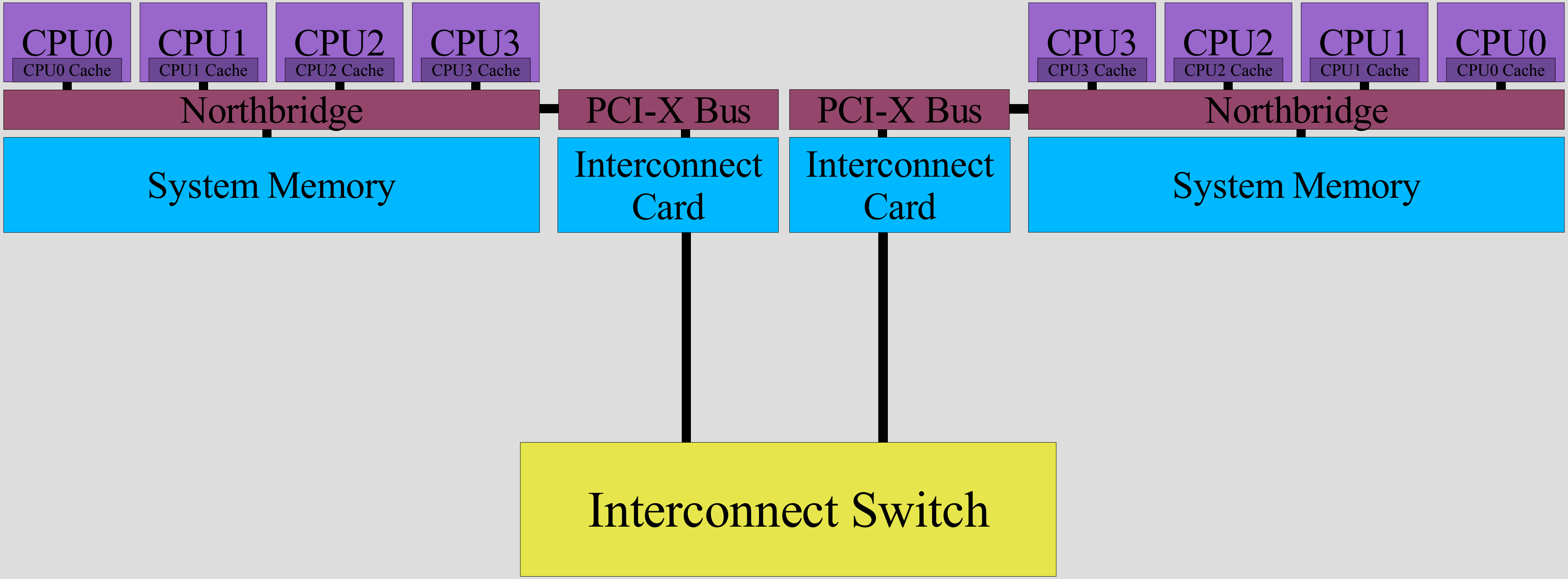
# Simplified NUMA Diagram Quad AMD Opteron



# Not SMPng: Graphics Processing Units (GPUs)



# Not SMPng: Loosely Connected Computation Clusters



# What is shared in an SMP System?

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

- Sources of asymmetry
  - Hyper-threading (HTT): physical CPU cores share computation resources and caches
  - Non-Uniform Memory Access (NUMA): different CPUs may access 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 to a lot of different people
  - 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, ...

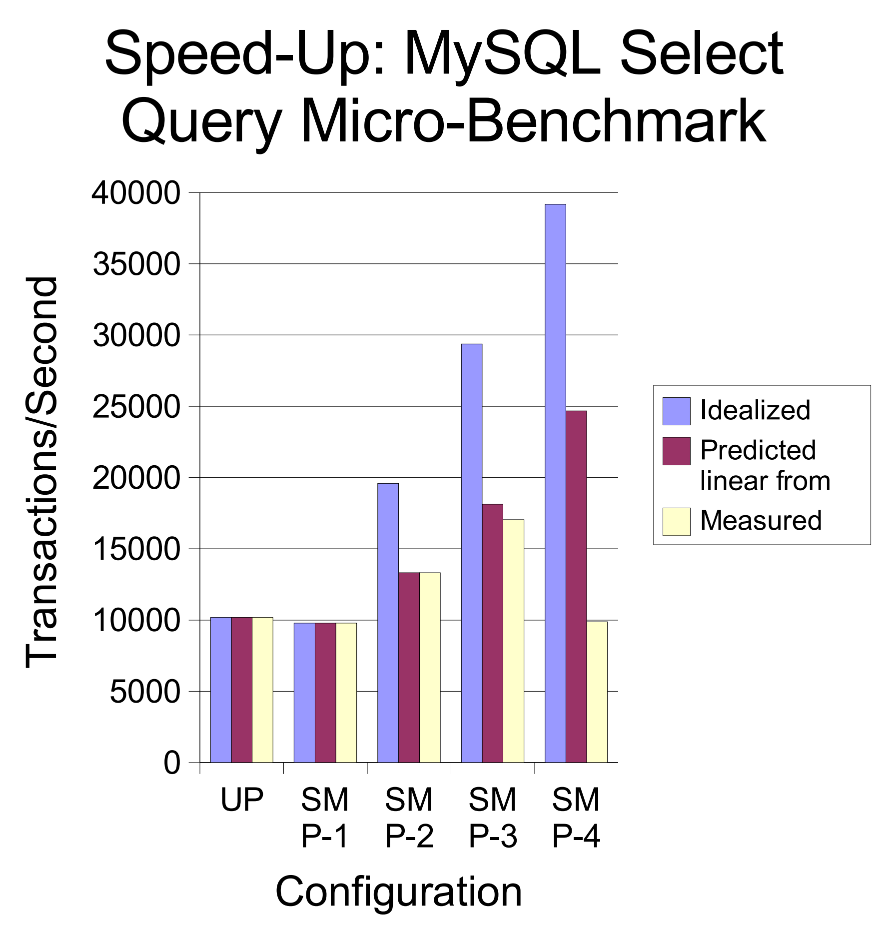
# OS Approach: Single System Image (SSI)

- To the extent possible, maintain the appearance of a single-processor system
  - Only with more CPU power
- Maintain current UNIX process model
  - Offer parallelism between user processes
  - Use threads as expression of single process parallelism
  - Requires minimal changes to applications yet offer significant performance benefit
- Because the APIs and services weren't designed for MP, has some challenges

# Definition of Success

- Goal is performance
  - Why else buy more CPUs?
  - However, performance is a nebulous concept
  - Very specific to workload
- “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

# Bootstrapping

- Not all that interesting
- The boot strap processor (BSP) starts up like any UP system
- The kernel “discovers” other CPUs
- Once sufficiently initialized, the kernel starts the additional processors (APs)

# 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

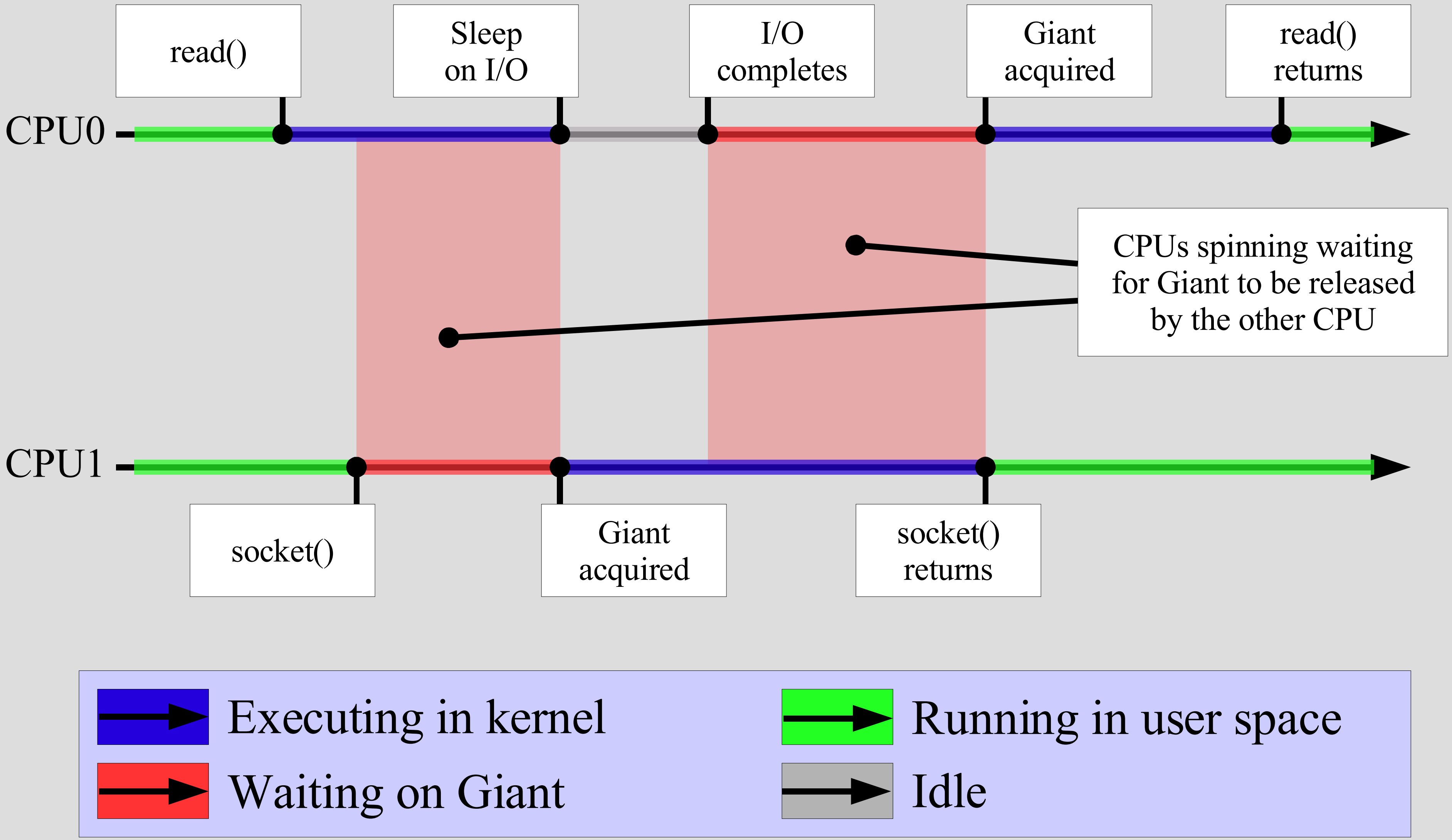
# Data Consistency

- 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)
  - Easiest way to get a UP system to run on MP hardware
  - Restore the assumption that the kernel runs on a single CPU at a time
  - Processors spin if waiting for the kernel
  - User processes or threads may run on more than one CPU at a time
  - Only one can enter the kernel at a time
- Easy to implement, but lots of “contention”
  - Synchronization costs are high
  - CPU is burned waiting for the kernel

# Context Switching in a Giant-Locked Kernel



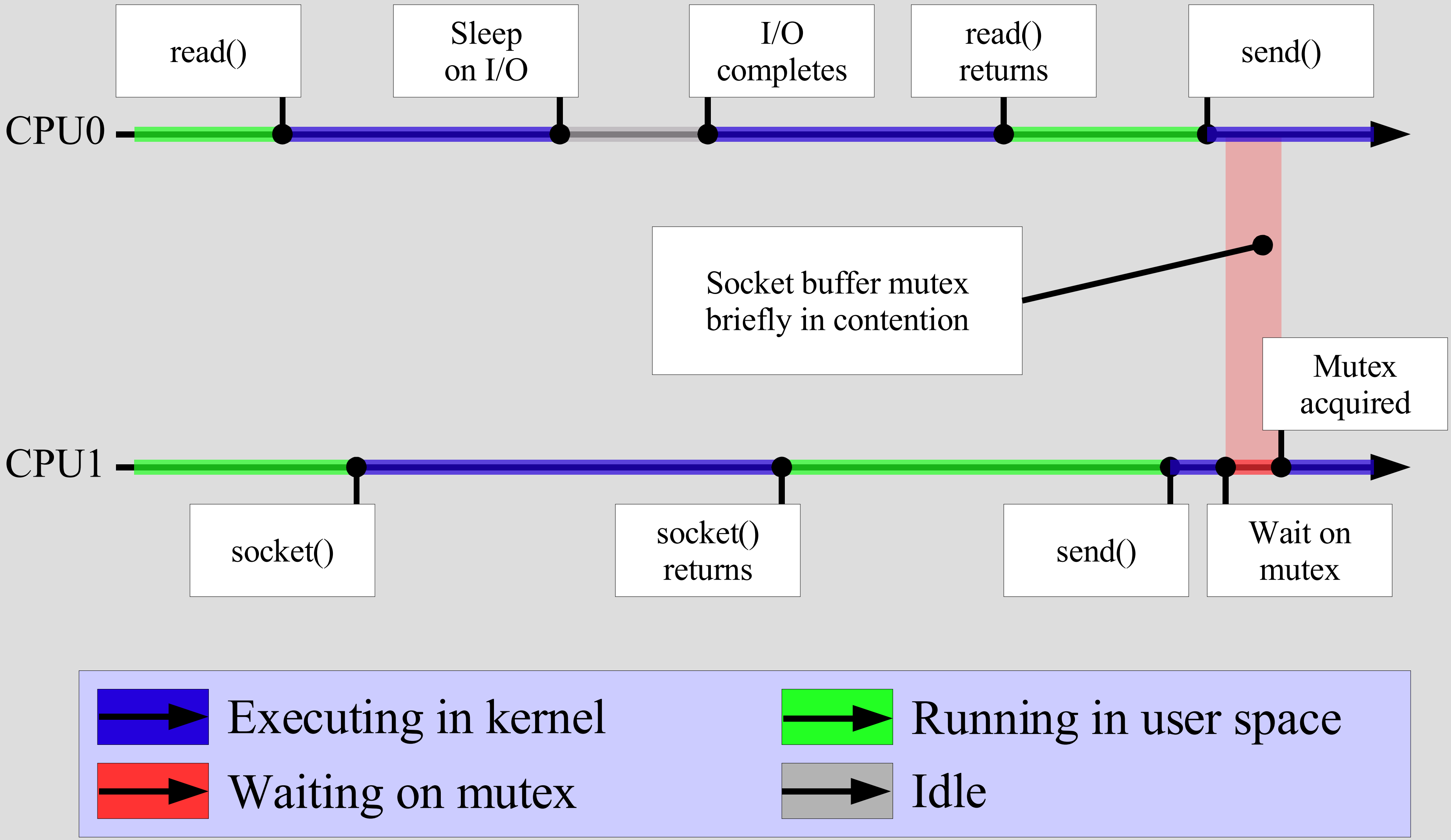
# The Problem: Giant Contention

- Contention in a Giant lock kernel occurs when events 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 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 the kernel
- Start with common dependencies
  - Synchronization, scheduling, memory allocation, timer events, ...

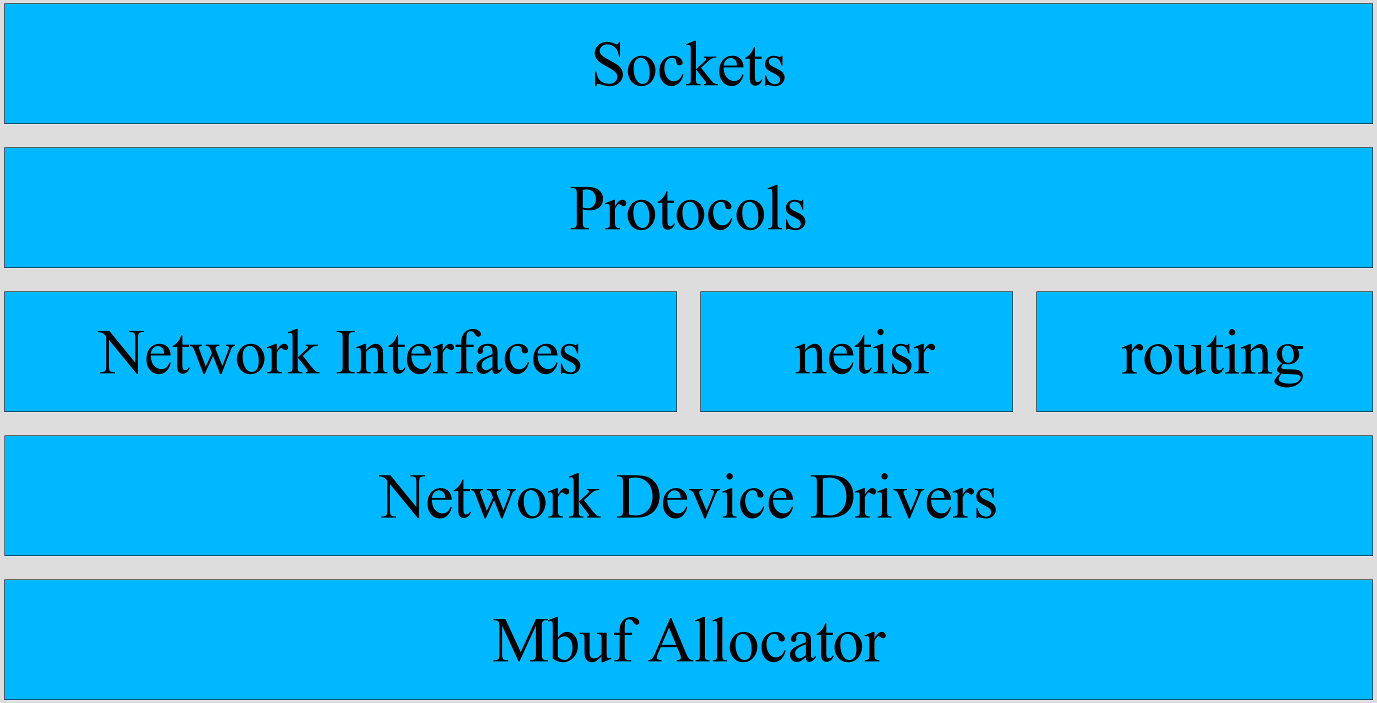
# FreeBSD Kernel

- 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
  - VFS also executes Giant-free, although most file systems are not

# Network Stack Components

- Over 400,000 lines of code
  - Excluding distributed file systems and device drivers
- Several significant components
  - “mbuf” memory allocator
  - Network device drivers
  - Net* protocols layer
    - Includes IPv4, IPv6, IPX, EtherTalk, ATM
  - Sockets and socket buffers
  - Netgraph extension framework

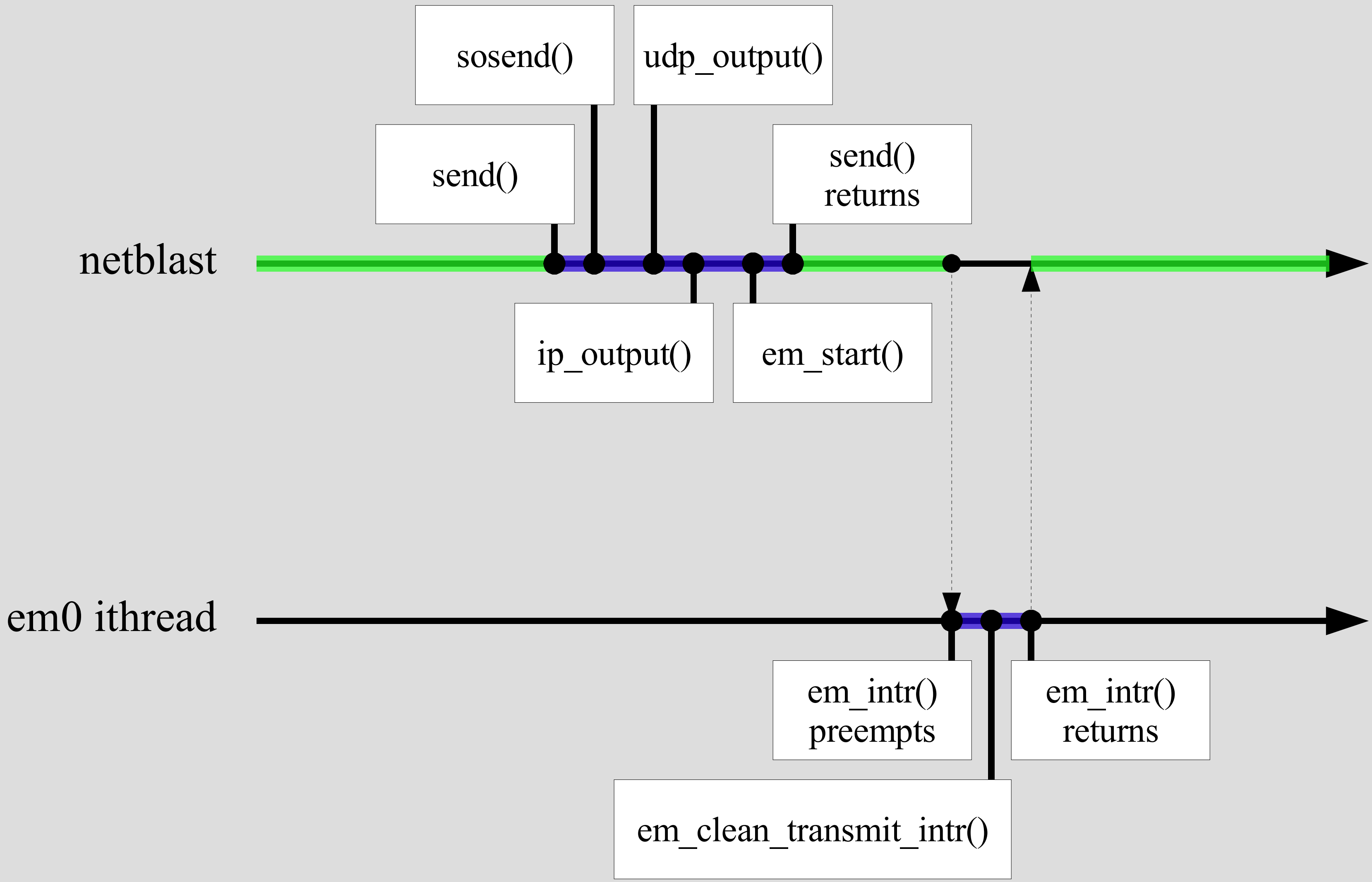
# FreeBSD Network Stack Components



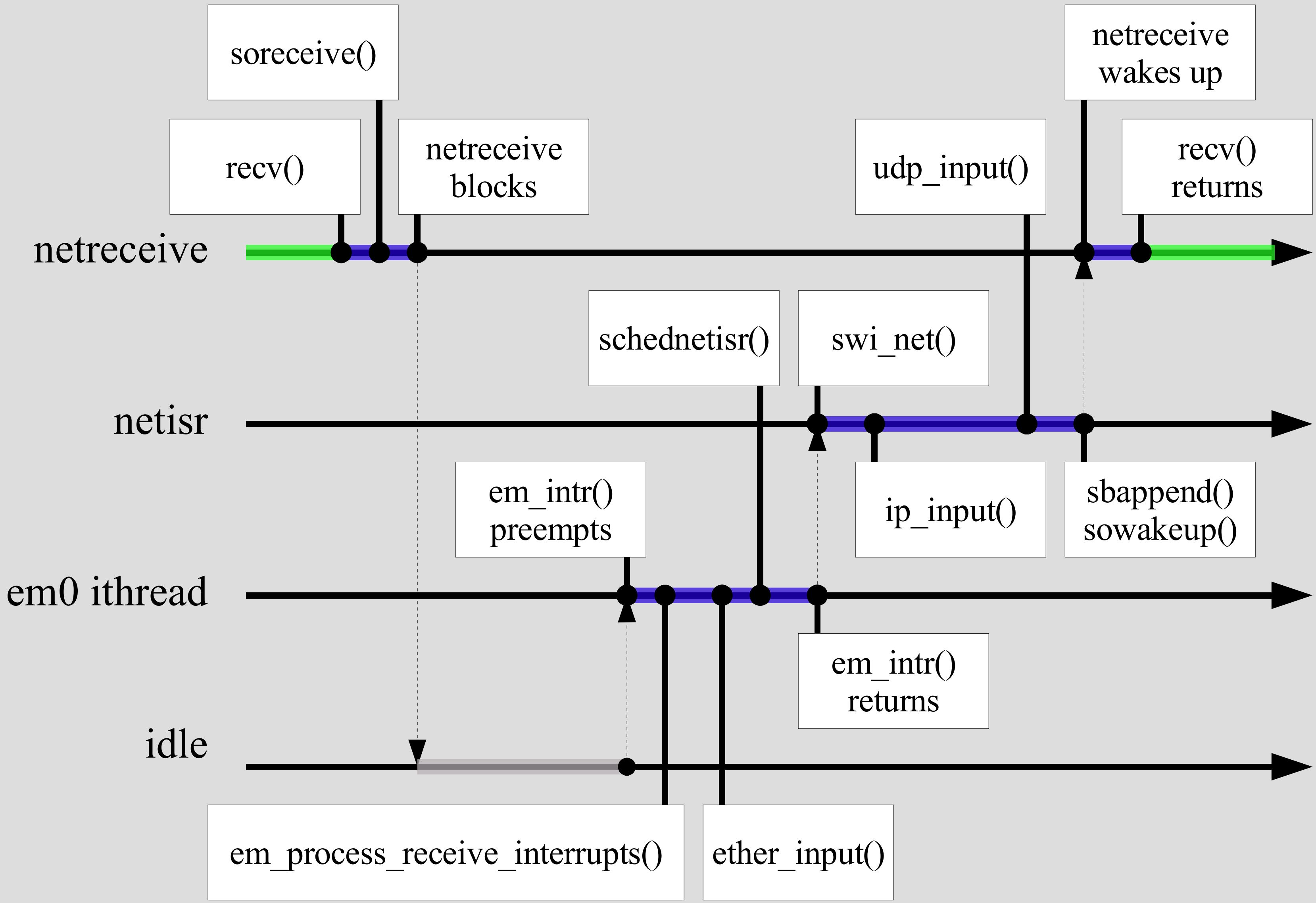
# Sample Data Flow TCP Send and Receive

| | | |
|---|---|---|
| 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 | 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, due to fast retransmit behavior
- 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 themselves
- Lock orders
  - Protocol drives most inter-layer activity
  - Acquire protocol locks before driver locks
  - Acquire protocol locks before socket locks

# Network Stack Parallelism

- Network stack was already threaded in 4.x
  - 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 – i.e., unbalanced CPU use?
- Identify natural boundaries in processing
  - Protocol hand-offs, layer hand-offs, etc
  - Carefully consider ordering considerations
- Weigh trade-offs
  - Context switches are expensive
  - Locks can be expensive

# Challenge: 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: Maintaining Ordering

- Ordering of packets is critical to performance
  - TCP will misinterpret reordering as requiring fast retransmit
- Ordering constraints must be maintained across dispatch from multiple sources
  - I.e., packets sourced from a single network interface should be processed “in order”
- Carefully select an ordering
  - “Source ordering” is used widely in the stack
  - 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
  - Upcoming 5.4-RELEASE includes substantial optimizations, stability improvements, ...
  - 6.x will include substantial optimizations, VFS, ...
- Some URLs:

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