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Scheduler Activations: Effective Kernel Support for the User-Level Management of Parallelism

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Outline

- Background
- Problem Statement
- The Approach
- Related Works
- User-level Thread
- Kernel-level Thread
- Scheduler Activation
- Implementation
- Experimental Evaluation
- Summary

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Background

- Technologies Trend.
- Process vs. Thread, and Why Thread?
- User Mode vs. Kernel Mode
- User-Level Thread vs. Kernel-Level Thread

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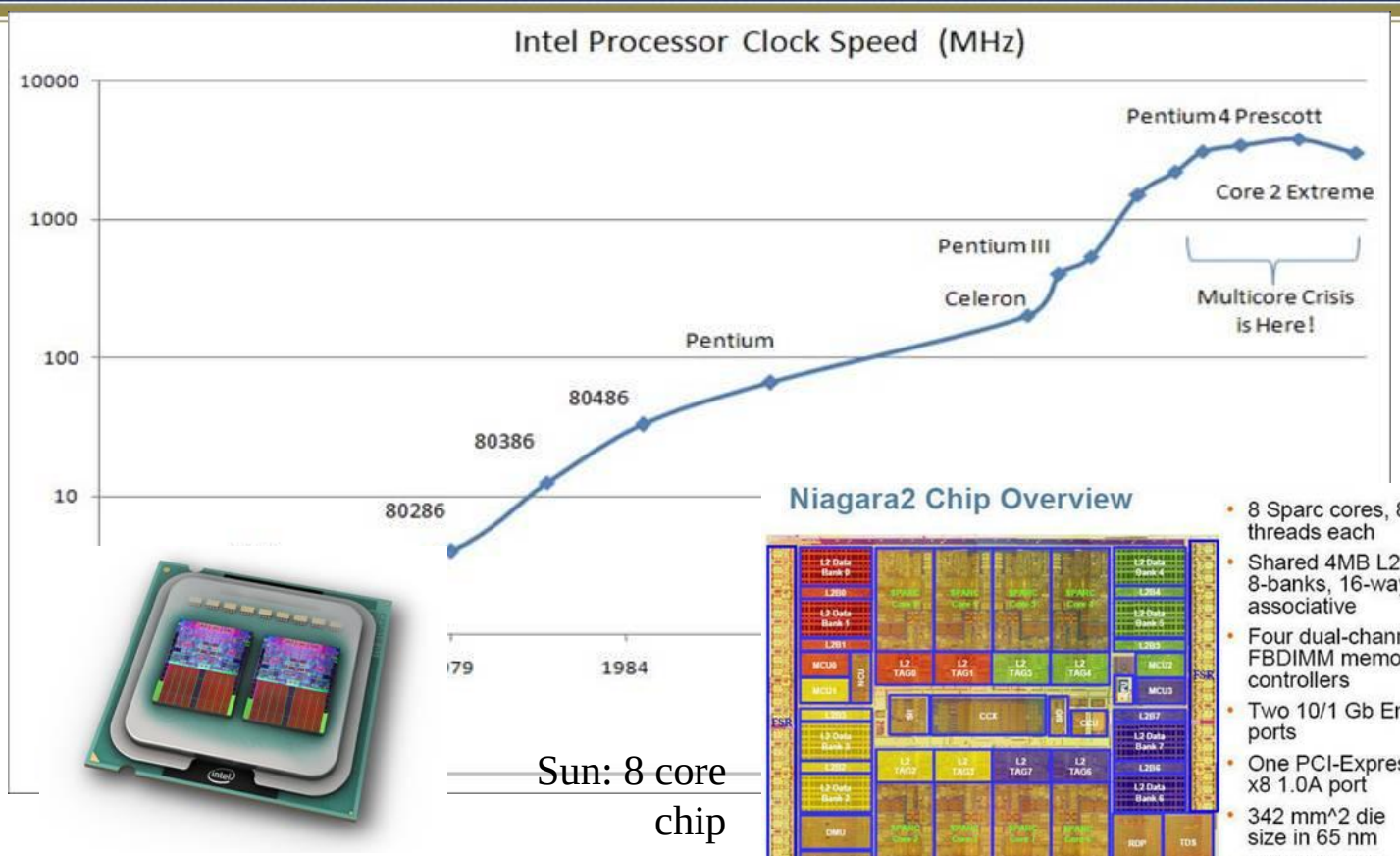
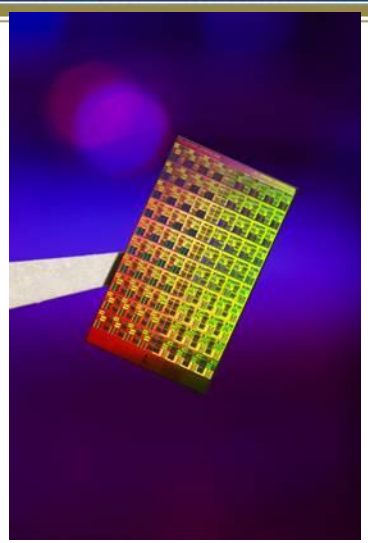
Technologies Driving Multi-Programming



Intel: Quad Core

Sun: 8 core chip



Intel: 80 core experimental system

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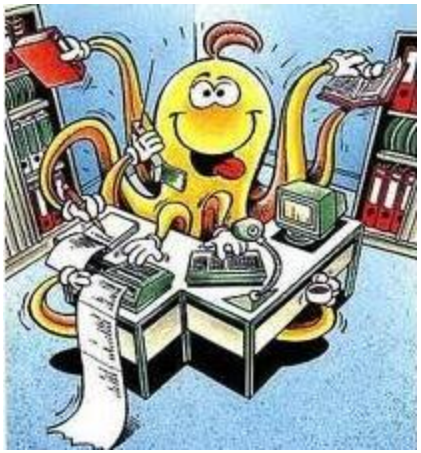
Reasons for Multi-Programming

performance

multitasking



parallelism

coordination

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Process vs. Thread

- Process is a program in execution, thread is a light-weight process.

	Process	Thread
Data Structure	PCB	TCB
Communication among processes/threads	Message, Shared Memory	Inherent Shared Memory
Time overhead	High	Low
Protection among processes/threads	Yes	No

Why Thread? An Example

- How to develop an editor that allow typo checking, document printing, and user input simultaneously?

Process based	Thread based
1 process for typo checking, 1 process for printing, 1 process for handling user input. **Explicitly leverage inter-process communication. Complicate!**	1 thread for typo checking, 1 thread for printing, 1 thread for handling user input. **Use shared data structure.**

User Mode vs. Kernel Mode

- **Kernel Mode**
  - Unrestricted access to hardware.
  - Execute trusted functions.
  - Crash is severe.
- **User Mode**
  - No ability to directly access hardware.
  - Crash is OK.

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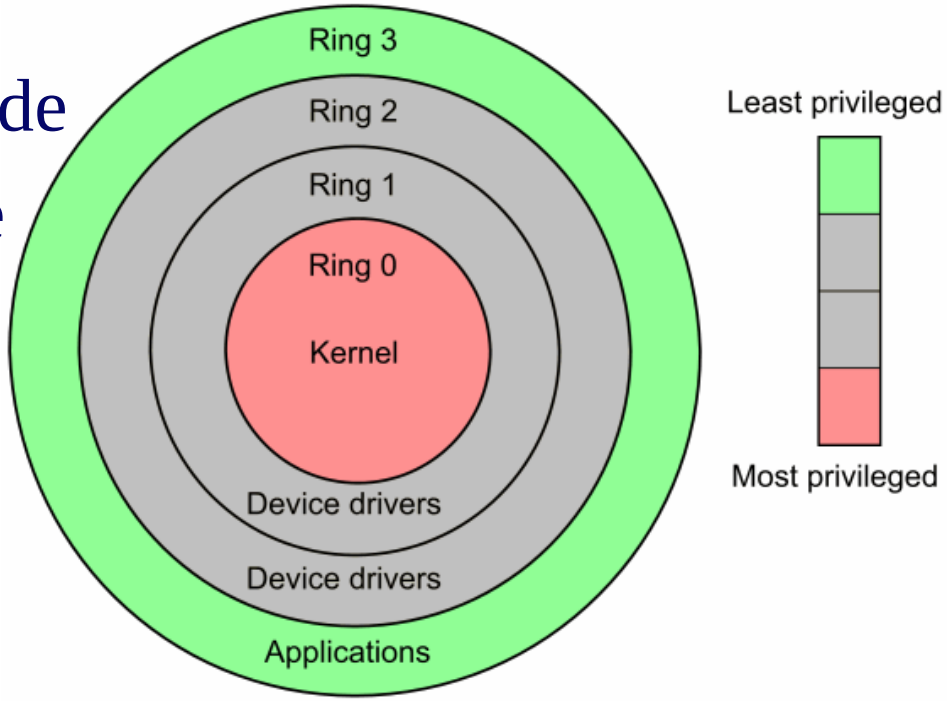
User Mode vs. Kernel Mode

- X86 architecture
  - Ring 0: kernel mode
  - Ring 3: user mode
  - Ring 1,2: driver?



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User-Level Threads vs. Kernel-Level Threads

- **User-level threads:** Build without any modifications to the underlying OS. Running on top of the system in user mode.
- **Kernel-level threads:** Build in kernel. Running directly in kernel mode.

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User-Level Threads vs. Kernel-Level Threads

	User-level threads	Kernel-level threads
Pros	1. No modification for kernel 2. Low overhead	Full-knowledge of all threads.
Cons	1. Threads in a process is invisible to the OS. 2. Block one thread would block whole process. 3. Access to multiple processors is not guaranteed.	1. High overhead. 2. Synchronization is more expensive.

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User-Level Threads vs. Kernel-Level Threads

- This paper is one of the pioneers that takes advantages from both user-level and kernel-level threads.

- Models: One-to-one, many-to-one, many-to-many, two-level. (See details later)

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Problem Statement

- Existing implementations
  - User-level choices: *PCR*, *FastThreads*
  - Kernel-level choices: threads support in *Mach*, *Topaz*, *V*

Dilemma of programmer

- Choose user-level threads
  - High performance.
  - Exhibit poor performance or incorrect behavior in presence of I/O, page faults, preemption.
- Choose kernel-level threads
  - No system integration problem. Threads are directly scheduled by kernel.
  - Low performance.

Neither is good enough!

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What is an ideal design?

- Functionality
  - No idled process when ready threads exist.
  - No high-priority threads wait for low-priority threads.
  - Block a thread would not block whole process
- Performance
  - As fast as user-level threads
- Flexibility
  - User-level part enables application-specific customization.

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The Approach

- A hybrid threads design.
  - Threads are implemented in both user-level and kernel-level . Only transmit necessary information between user-level and kernel-level.
- Each application:
  - Provided with a virtual multiprocessor.
  - Has full knowledge about the allocated processors.
  - Can control which threads run on which processor.

The Approach

- Communicating upward
  - Improve functionality
- Communicating downward
  - Preserve performance

Scheduler activations: The execution context for an event vectored from the kernel to an address space.

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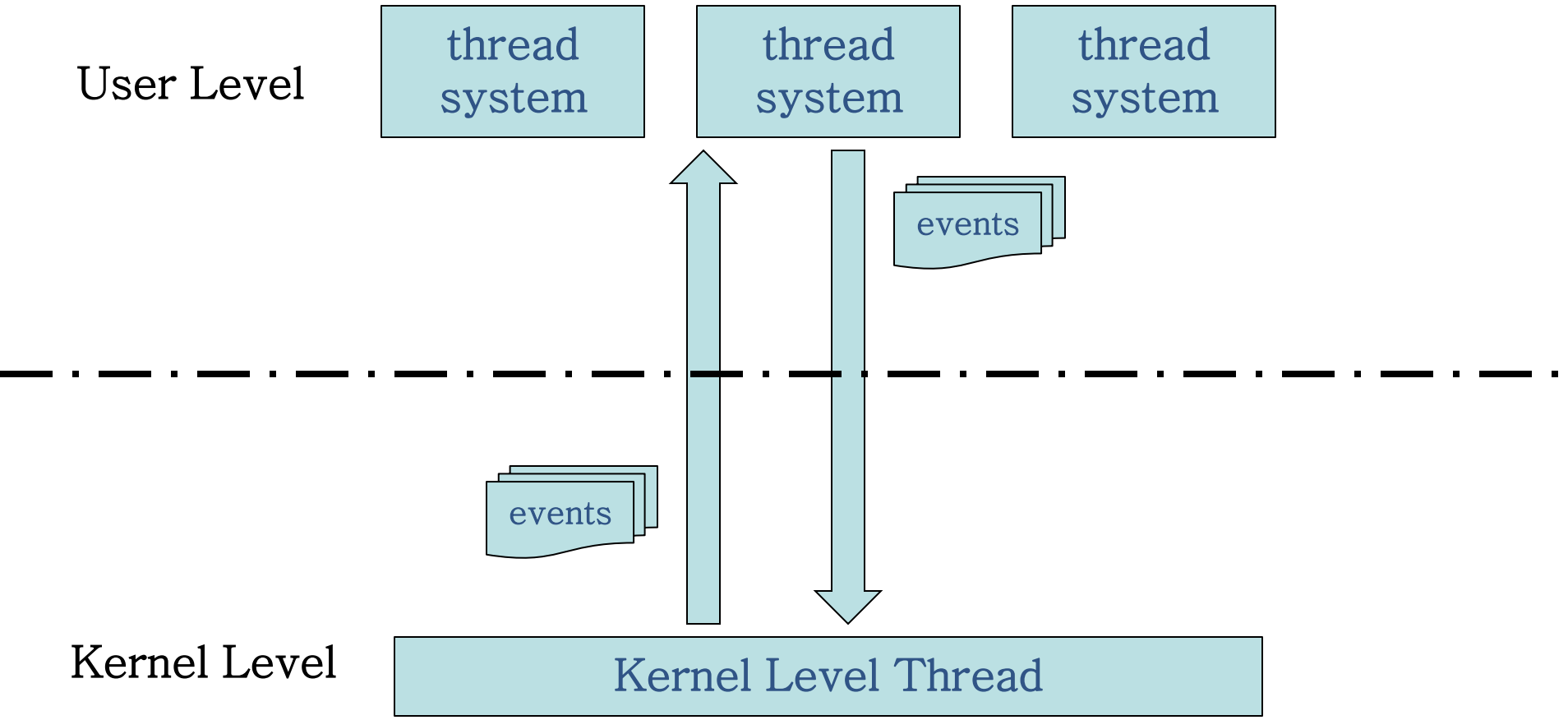
The Approach



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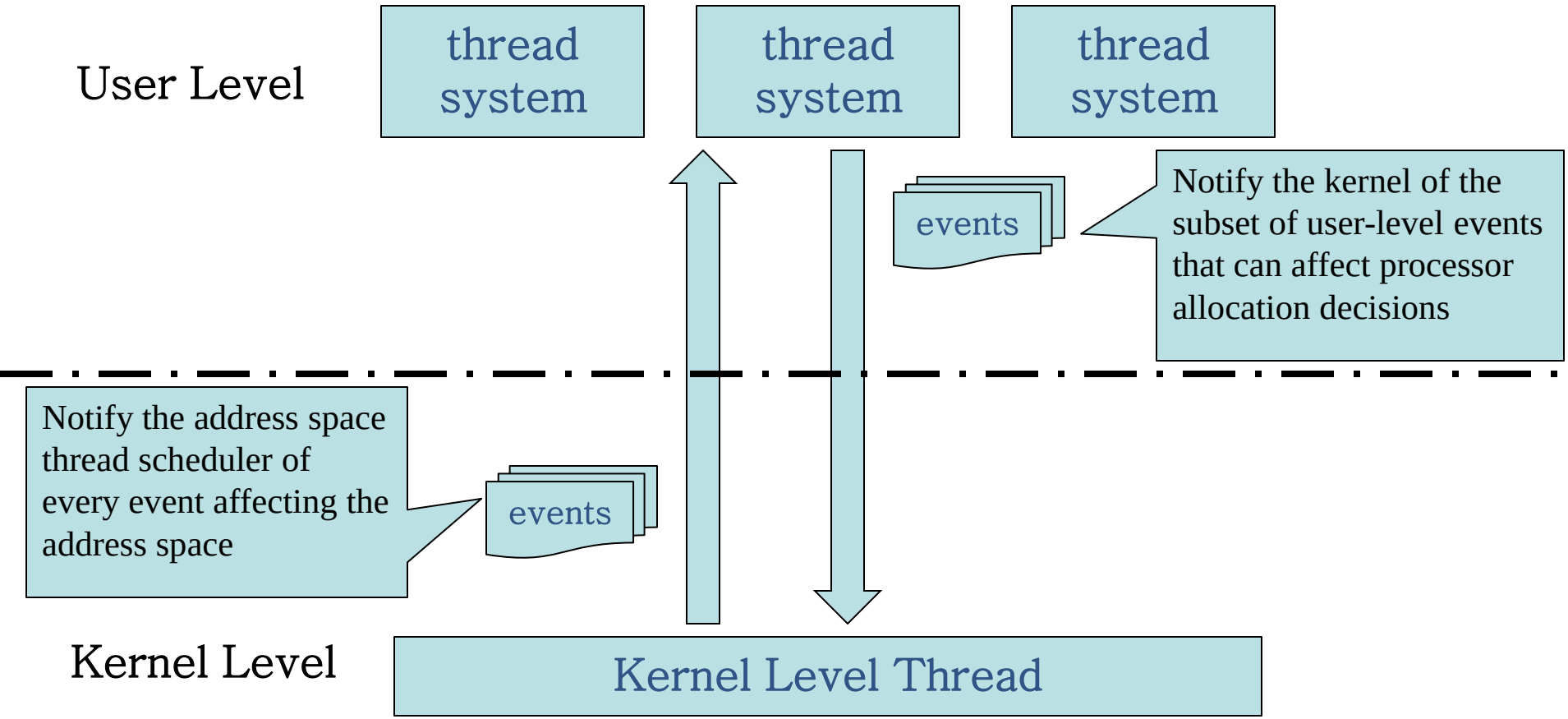
The Approach



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Related Works

- Psyche and Symunix

	Scheduler Activations	Psyche and Symunix
Platform	Topaz (UNIX)	Psyche: UNIX Symunix: New OS
Communication	Between user-level and kernel-level	Between kernel and application
Synchronization	Low overhead	High overhead, Should be handled between applications and kernel

Related Works

- Compare with traditional asynchronous I/O system.
  - Uniformly addresses preemption, I/O, and page faults.
  - No need to major change the structure for application and kernel code.

Related Works

- Compare with Hydra
  - Both implement scheduling policy out of kernel.
  - Hydra: scheduling requires coordinating between scheduler server and kernel. Scheduler Activation: Scheduling is autonomic.

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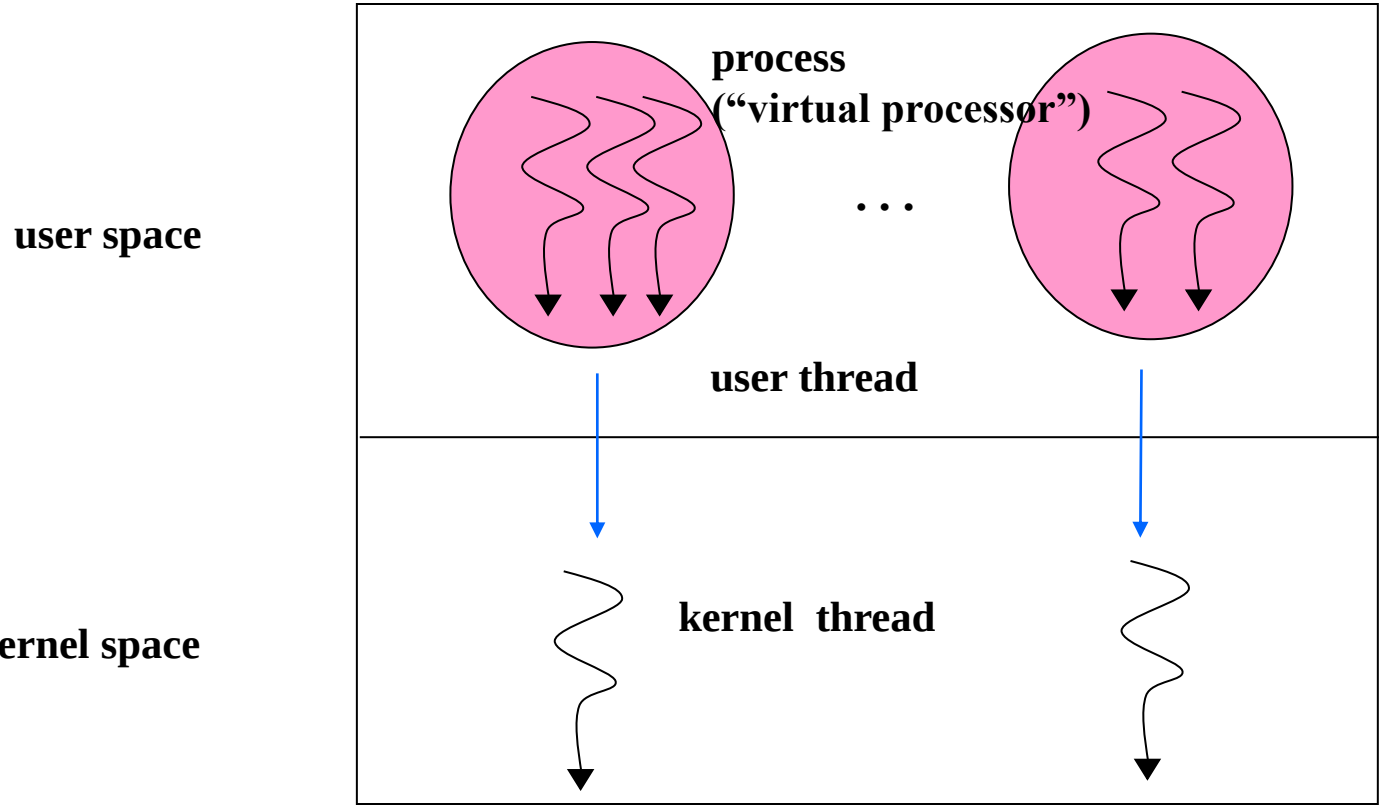
User-level Thread



User-level Thread

- **Divide up the process resources between threads.**
  - N:1 arrangement, with N user threads sharing one kernel thread.
  - Managed by runtime library routines.
  - Require no kernel intervention.
- **E.g.: GNU PTH Thread Library, FSU Threads.**
- **The thread package views each process as a virtual processor.**
  - Each virtual processor runs user-level code that pulls threads off the ready queue and runs them.

Advantages of User-level Threads

- **Occupy the user address space of the process.**
  - No overhead of kernel intervention when switching between threads.
  - Not much more expensive than a regular procedure call.
- **Flexible and amenable to specialization.**
  - Only need to meet the requirements of the specific applications that will use them.
    - If priority scheduling is not needed, for example, leave it out.

Disadvantages of User-level Threads

- **There is a lack of kernel support in existing systems.**
  - A process gets the same amount of time regardless of how many threads it is running.
  - System is not able to make use of multiprocessors.
- **Kernel threads block, resume, and are preempted without the user level threads being notified.**
  - Page faults, I/O can block the whole process.
    - Poor performance or cause errors.

Example: I/O

- **One application running five user-level threads.**
  - Performs inexpensive application-level context switches between threads.
- **Thread3 performs a system call for a file read().**
  - Kernel blocks the whole process, including the remaining four threads that are waiting to run.
- **Solution?**
  - Application intercepts system calls and substitutes an asynchronous (nonblocking) call.
    - An asynchronous interface call appears to return control to the caller immediately. Results will arrive later.
    - The remaining threads can now be run while thread3 is blocked.
  - Page faults cannot be predicted and mitigated, however, and will also result in the whole process being blocked.

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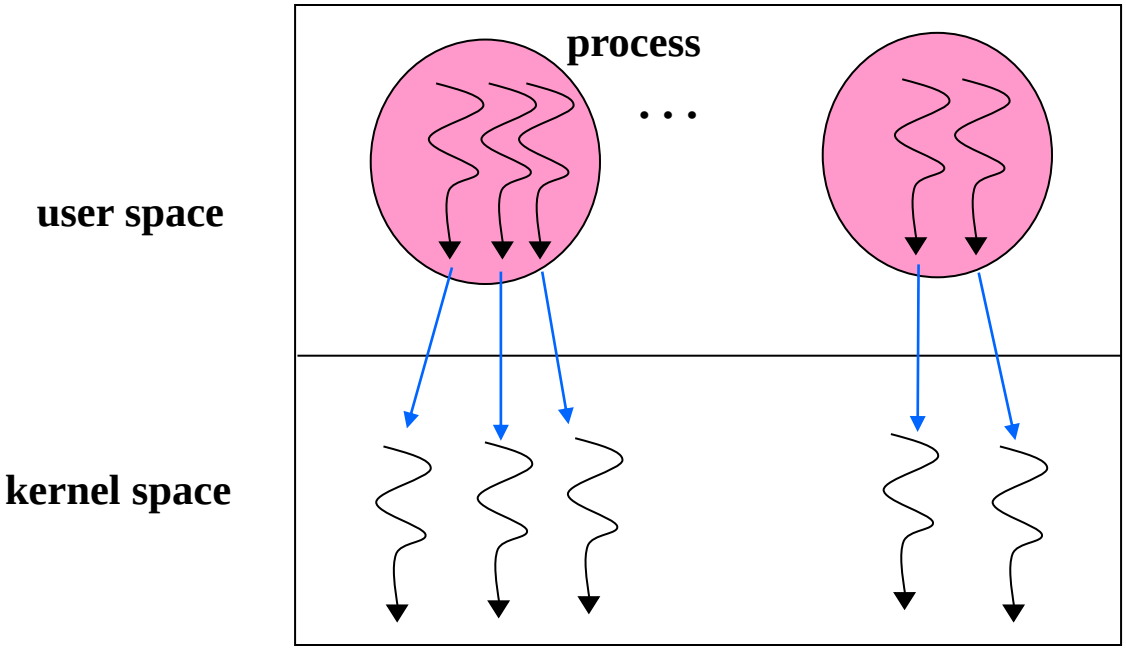
Kernel-level Thread



Kernel-level Thread

- **Kernel threads directly schedule each processes threads onto physical processors.**
  - 1:1 arrangement, each application threads maps to one kernel thread.
  - Enjoy direct OS support, so lack the problems that hinder user-level thread reliability.
- **E.g.: Linux, IRIX, Windows NT.**
- **Too much overhead to use in many parallel programs.**
  - Performance isn't as good as that of user threads.

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Advantages, Disadvantages of Kernel-level Threads

- **Kernel is aware of the threads.**
  - Scheduler can assign time to processes based on the number of threads they carry.
  - I/O, page faults, and interrupts are not a problem.
  - Supports the needs of any application that runs it.
- **Hundreds of times slower than user-level threads.**
  - Kernel threads use system calls to perform operations.
    - Switching between threads requires a full context switch.
  - Kernel threads are heavyweights, must support every need of an application.
  - Each kernel thread consumes kernel memory.

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N:M Thread System

Goal: System with the functionality of kernel threads and the performance and flexibility of user-level threads.

- Maps some no. N of application threads onto a no. M of kernel entities (usually N>M).
- N:M thread systems are more complicated and effective
- Implemented by associating groups of threads with single kernel entities.
- Both AIX and Solaris use N:M thread system.

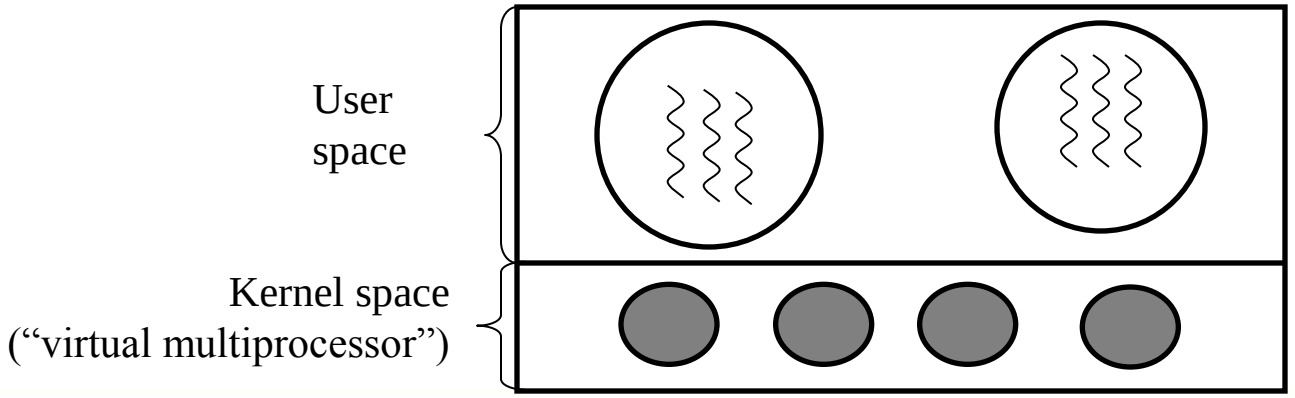
Problem

- Application has knowledge of the user-level thread state but has little knowledge of or influence over critical kernel-level events (by design! to achieve the virtual machine abstraction)
- Kernel has inadequate knowledge of user-level thread state to make optimal scheduling decisions

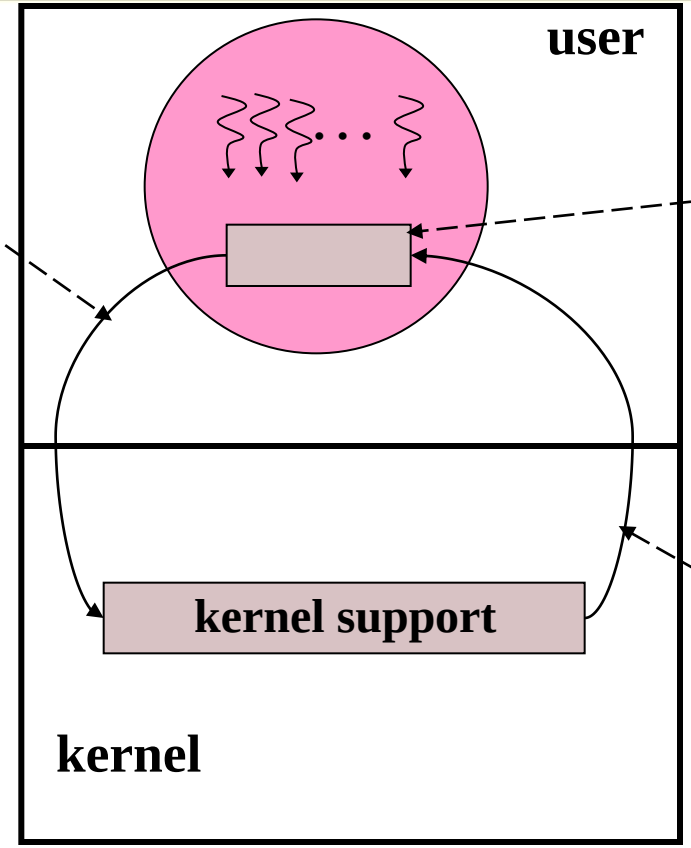
Solution: a mechanism that facilitates exchange of information between user-level and kernel-level mechanisms.

Virtual Multiprocessor

- **Application knows how many and which processors allocated to it by kernel.**
- **Application has complete control over which threads are running on processors.**
- **Kernel notifies thread scheduler of events affecting address space.**
- **Thread scheduler notifies kernel regarding processor allocation.**



Scheduler Activations: Structure



- Change in processor requirements

thread library

Scheduler activations

- change in processor allocation
- change in thread status

Scheduler Activations

- **Structure to provide communication between the kernel processor and the user-level thread system.**
- **A scheduler activation:**
  - Takes the place of a kernel thread as an execution context for user-level threads.
  - Notifies the user-level thread system of kernel changes.
  - Provides space in the kernel for storing the processor context when the thread is swapped out.

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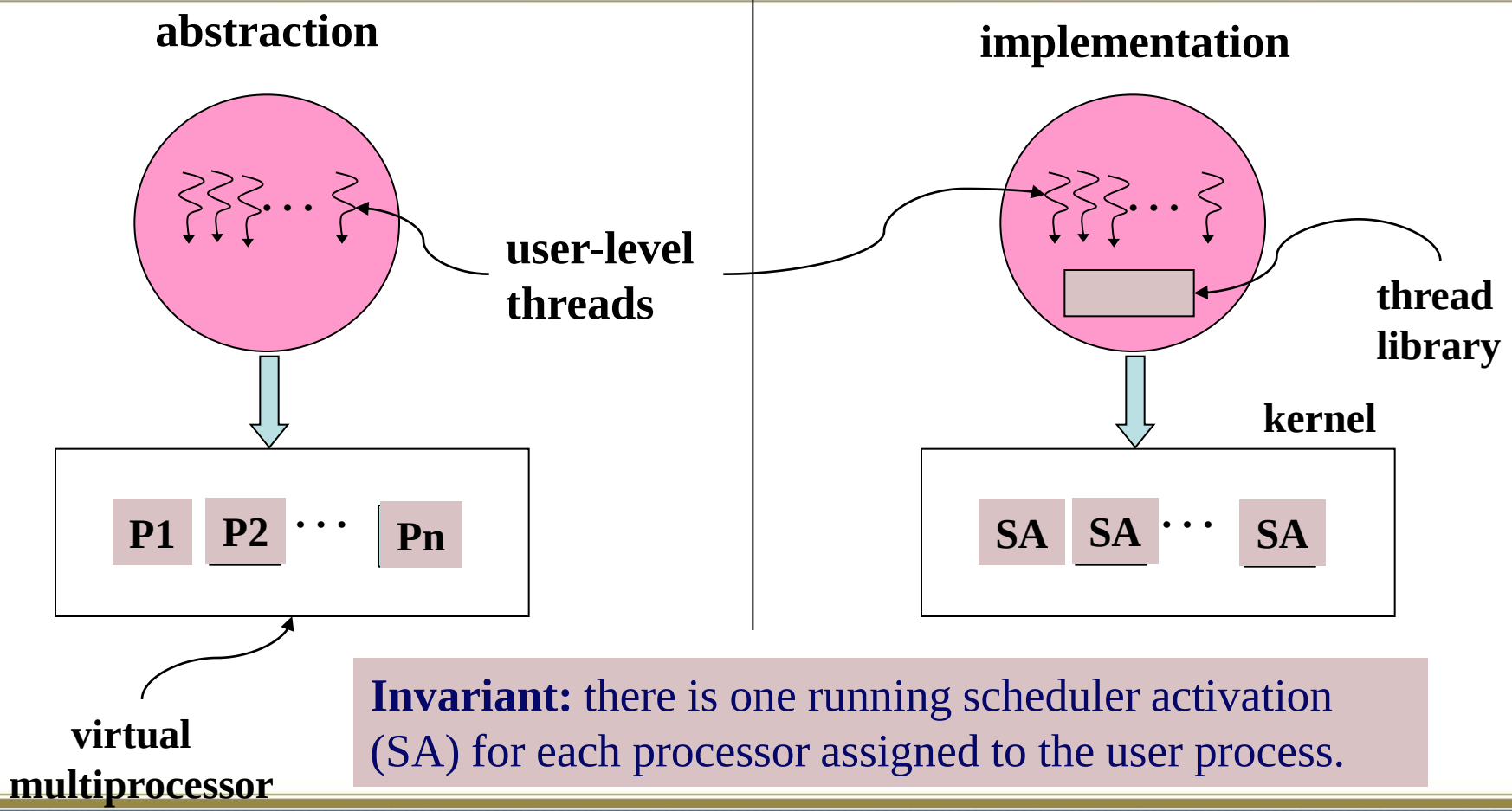
Scheduler Activations

- **The kernel provides each user-level thread system with its own virtual processor.**
  - Kernel has control over how many processors to give.
    - Each user-level thread system chooses which threads to run on it's allocated processors.
    - Kernel notifies the user-level thread system of any changes, through the scheduler activation.
      - processors assigned, I/O interrupts, page faults.
- **One scheduler activation per processor assigned to address space.**

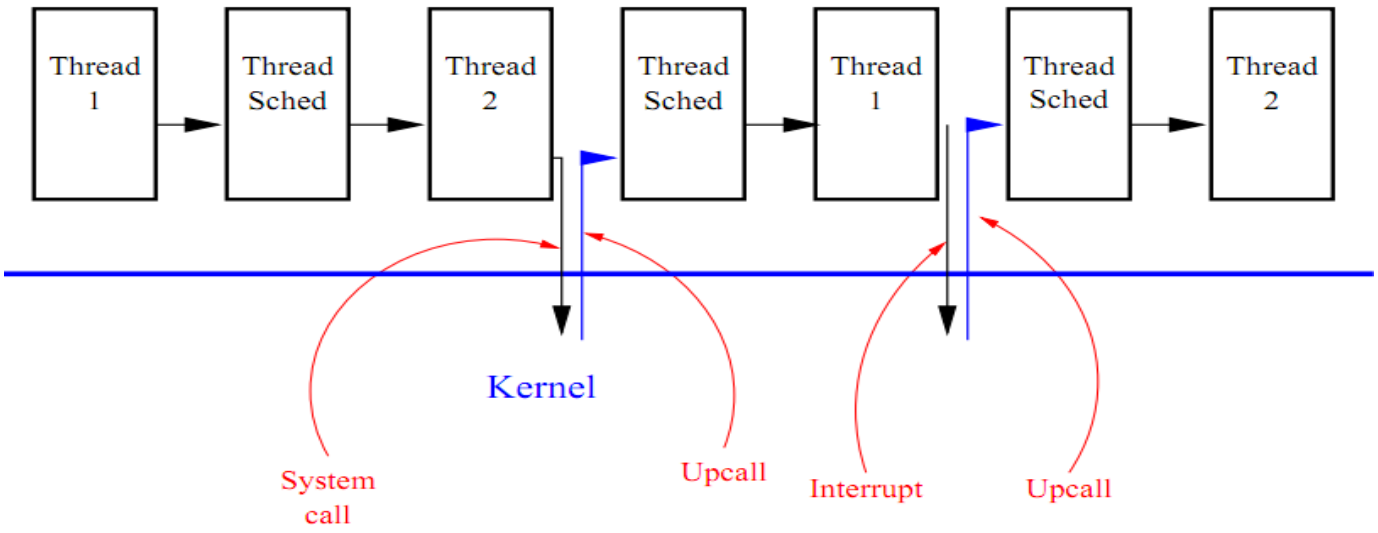
Role of Scheduler Activations



Invariant: there is one running scheduler activation (SA) for each processor assigned to the user process.

Communication via Upcalls

The kernel-level scheduler activation mechanism communicates with the user-level thread library by a set of upcalls:



Communication : Kernel to User Level

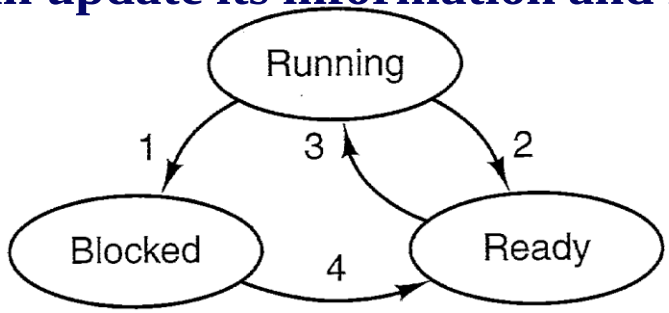
- **Add this processor** (processor #)
  - *Execute a runnable user-level thread.*
- **Processor has been preempted** (preempted activation # and its machine state)
  - *Return to the ready list the user-level thread that was executing in the context of the preempted scheduler activation.*
- **Scheduler activation has blocked** (blocked activation #)
  - *The blocked scheduler activation is no longer using its processor.*
- **Scheduler activation has unblocked** (unblocked activation # and its machine state)
  - *Return to the ready list the user-level thread that was executing in the context*

Communication : Kernel to User Level

Notice that these four messages correspond neatly with this graph.

- It shows the different states a process or kernel thread can be in: running, ready to run, or blocked.
- Whenever a kernel thread system would change the state of a thread "transparently", scheduler activations contact the user-level scheduler.

It can update its information and rethink.



1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

Figure 2-2. A process can be in running, blocked, or ready state. Transitions between these states are as shown.

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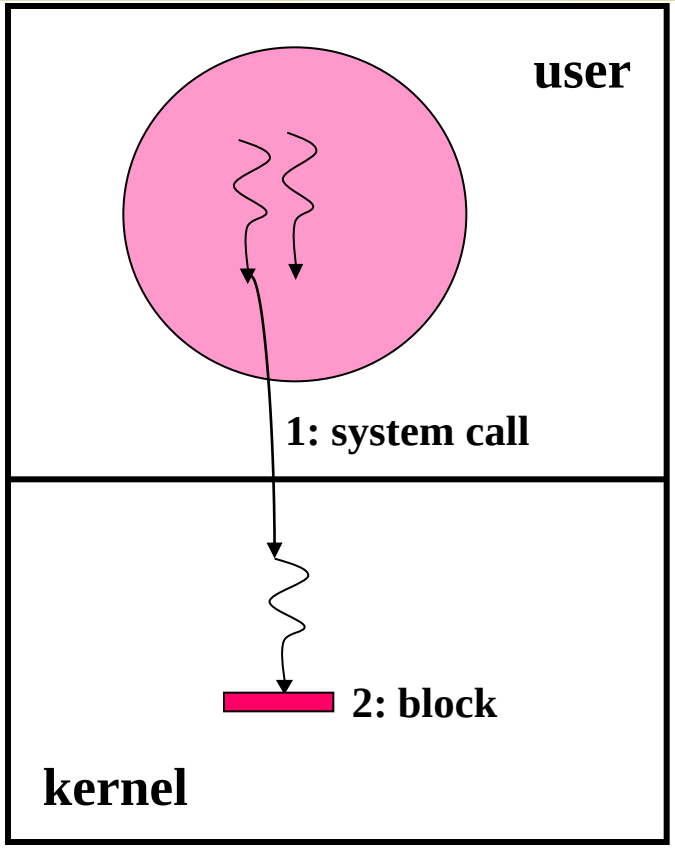
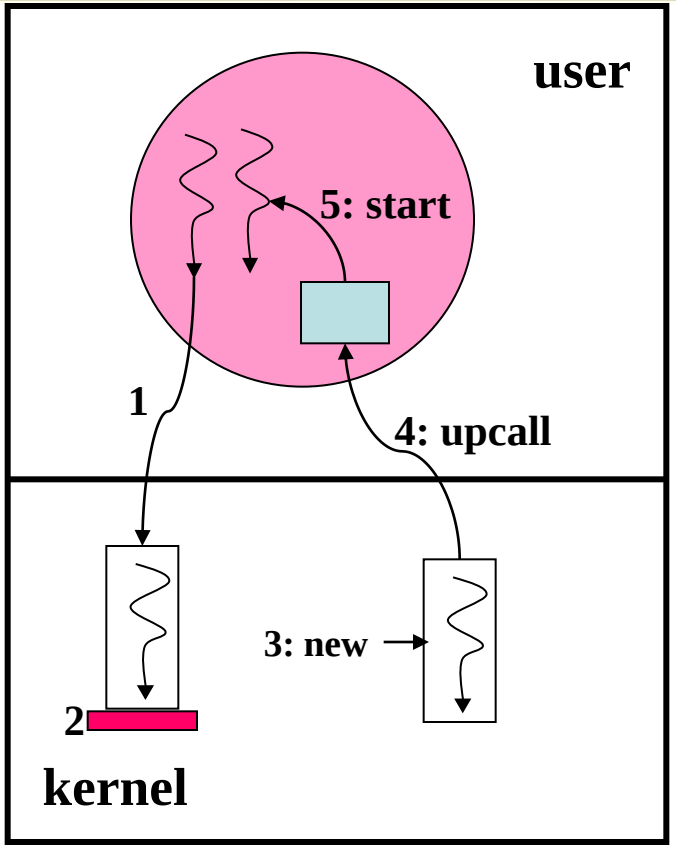
Avoid Effects of Blocking

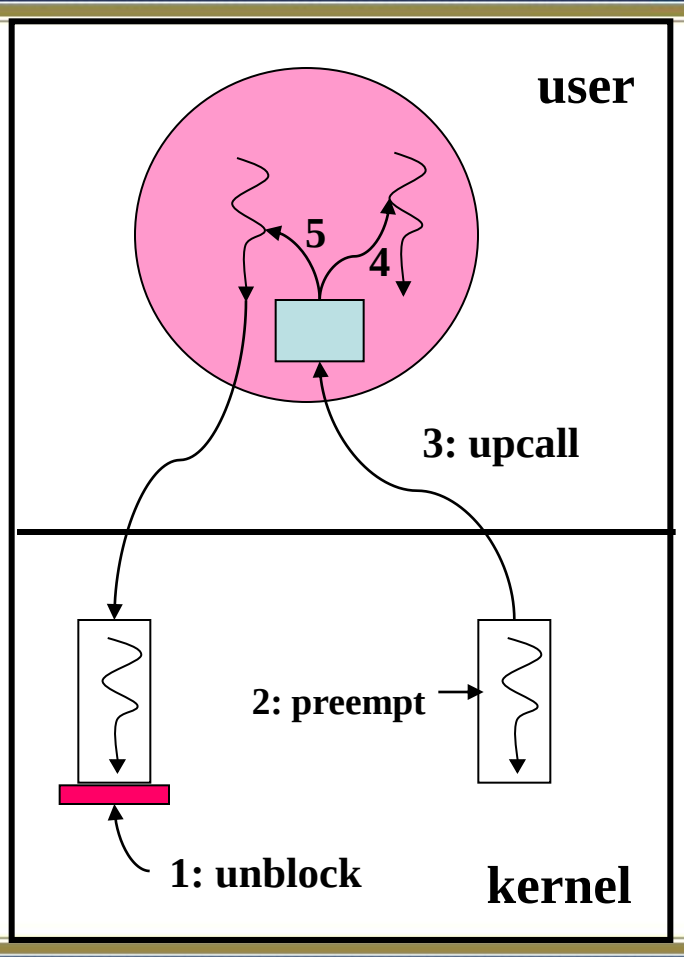


Kernel threads



Scheduler Activations

Resuming Blocked Thread



4: preempt
5: resume

Communication : User Level to Kernel

- **#Runnable Threads != # Processors**
- **Add more processors (additional # of processors needed)**
  - Allocate more processors to this address space and start them running scheduler activations.
- **This processor is idle ()**
  - Preempt this processor if another address space needs it.

Critical Sections

- **A user-level thread can be preempted while it is executing a critical section.**
  - Could result in deadlock or performance drop.
- **If a thread that has been preempted was executing a critical section, a user-level context switch is necessary.**
  - Thread continues temporarily, finishes its critical section, and then relinquishes control back to the upcall.
- **Implemented by making a copy of each low-level critical section.**
  - In the copy, code is added to yield the processor back to the resuming thread.
  - If a preemption occurs, the kernel resumes the thread in the corresponding place in the copy.

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Example: Managing I/O

T1: The application receives two processors to run on from the kernel.

It starts running threads on them.

T2: One of the user-level threads blocks in the kernel.

Kernel uses a fresh scheduler activation to notify the user-level system of this.

T3: The blocking-event completes. Kernel preempts second processor to do the upcall.

Upcall notifies user level of upcall and of event completion.

T4: Upcall takes the thread from the ready list and begins running it.

The first two scheduler activations have now been discarded and replaced.

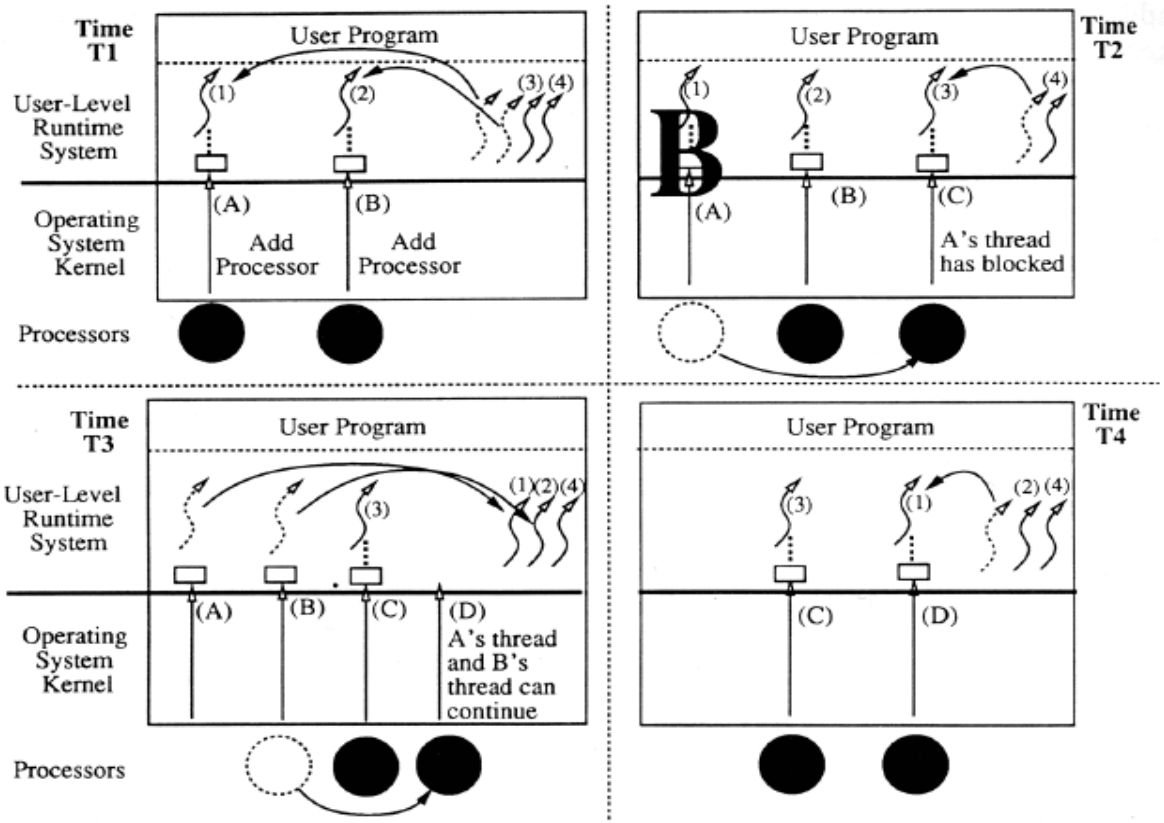

Fig. 1. Example: I/O request/completion.

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Implementation

- Modification of Topaz Operating System
- Topaz is OS for DEC SRC Firefly a mutli-processor workstation
- Modification of FastThreads a user level thread package
- Lines of code used

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Implementation

Implementation Sections

- Processor Allocation Policy
- Thread Scheduling Policy
- Performance Enhancement
- Debugging Considerations

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Processor Allocation Policy

- Similar to dynamic policy of Zahorjan and McCann using Space-Shares
- Possible for address space to use kernel threads
- Support for Topaz kernel threads
- No need for static partitioning of processors

Thread Scheduling Policy

- Kernel has not knowledge of an application's concurrency model or scheduling policy
- Applications has freedom to decide how to handle scheduling
- FastThreads use of per processor ready lists with Last In First out order

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Thread Scheduling Policy

- Hysteresis used to avoid unnecessary processor reallocation
- Hysteresis Example

Performance Enhancement

- Critical sections
  - Typical solution using flags. Disadvantage: has overhead
  - Solution used, similar to Trellis/Owl garbage collector. Advantage: no overhead in common case

Performance Enhancement

- Management of scheduler activations
  - Unused scheduler activations can be cached for reuse
  - Scheduler activation sent in bulk for reuse

Debugging Considerations

- Firefly Topaz Debugger
  - User level
  - Application

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Experimental Evaluation

- Three questions
  - What is the cost of user-level thread operations
  - What is the cost of communication between kernel and the user level
  - What is the overall effect on the performance of applications

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Experimental Evaluation

Experimental Evaluation Sections

- Thread Performance
- Upcalls
- Application Performance

Thread Performance

- Cost of user threads, same as FastThreads

Operation	FastThreads on Topaz threads	FastThreads on Scheduler Activations	Topaz threads	Ultrix processes
Null Fork	34	37	948	11300
Signal-Wait	37	42	441	1840

Table 4: Thread Operation Latencies (μsec.)

Upcall

- Measure of Upcall performance
  - Two user-level threads to signal and wait

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Application Performance

- Parallel Application using Topaz kernel threads
- Setup of application and modifications
- Procedure and methods.
- Comparison to FastThreads

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Application Performance

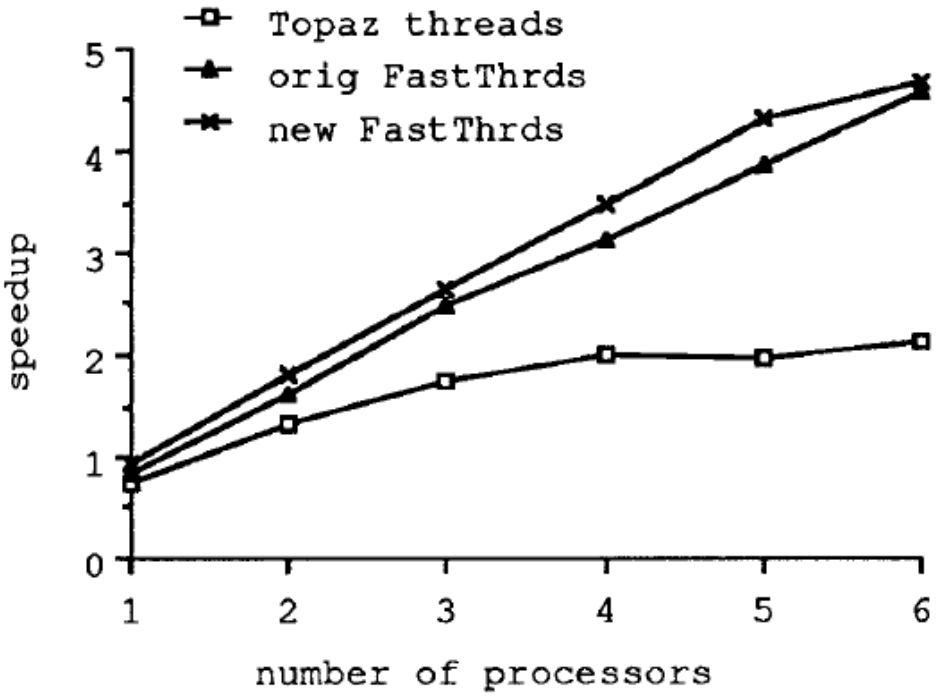

Figure 1: Speedup of N-Body Application vs. Number of Processors, 100% of Memory Available

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Application Performance

- Effect of performance application-induced kernel events
- Better performance than FastThreads

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Application Performance

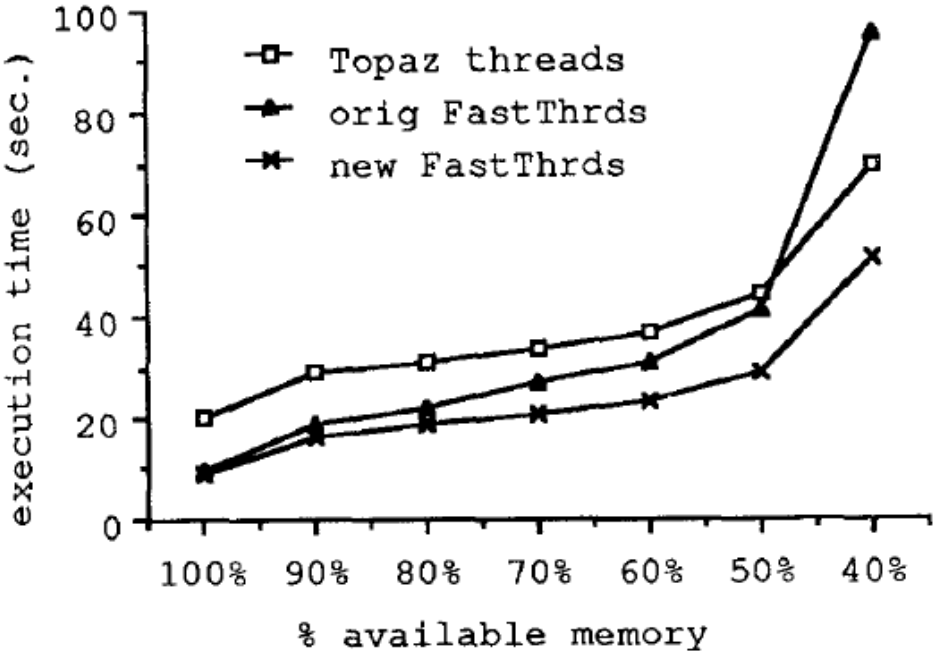

Figure 2: Execution Time of N-Body Application vs. Amount of Available Memory, 6 Processors

Application Performance

Topaz threads	Original FastThreads	New FastThreads
1.29	1.26	2.45

Table 5: Speedup for N-Body Application, Multiprogramming Level = 2, 6 Processors, 100% of Memory Available

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Summary

- Implement user-level thread package
- Virtual Multiprocessor in application address space
- Divided responsibilities

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Summary

- Processor allocation
- Thread Scheduling
- Kernel notifications to address space thread scheduler
- Address space notifications to kernel for processor allocations

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Questions?

- Questions?