Thread Scheduling

Roadmap for This Lecture

- Overview
- Priorities
- Scheduling States
- Scheduling Data Structures
- Quantum
- Scheduling Scenarios
- Priority Adjustments (boosts and decays)
- Multiprocessor Scheduling
- Lab Demo

Scheduling Criteria

- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – # of processes/threads that complete their execution per time unit
- **Turnaround time** – amount of time to execute a particular process/thread
- **Waiting time** – amount of time a process/thread has been waiting in the ready queue
- **Response time** – amount of time it takes from when a request was submitted until the first response is produced, **not** output (i.e.; the hourglass)

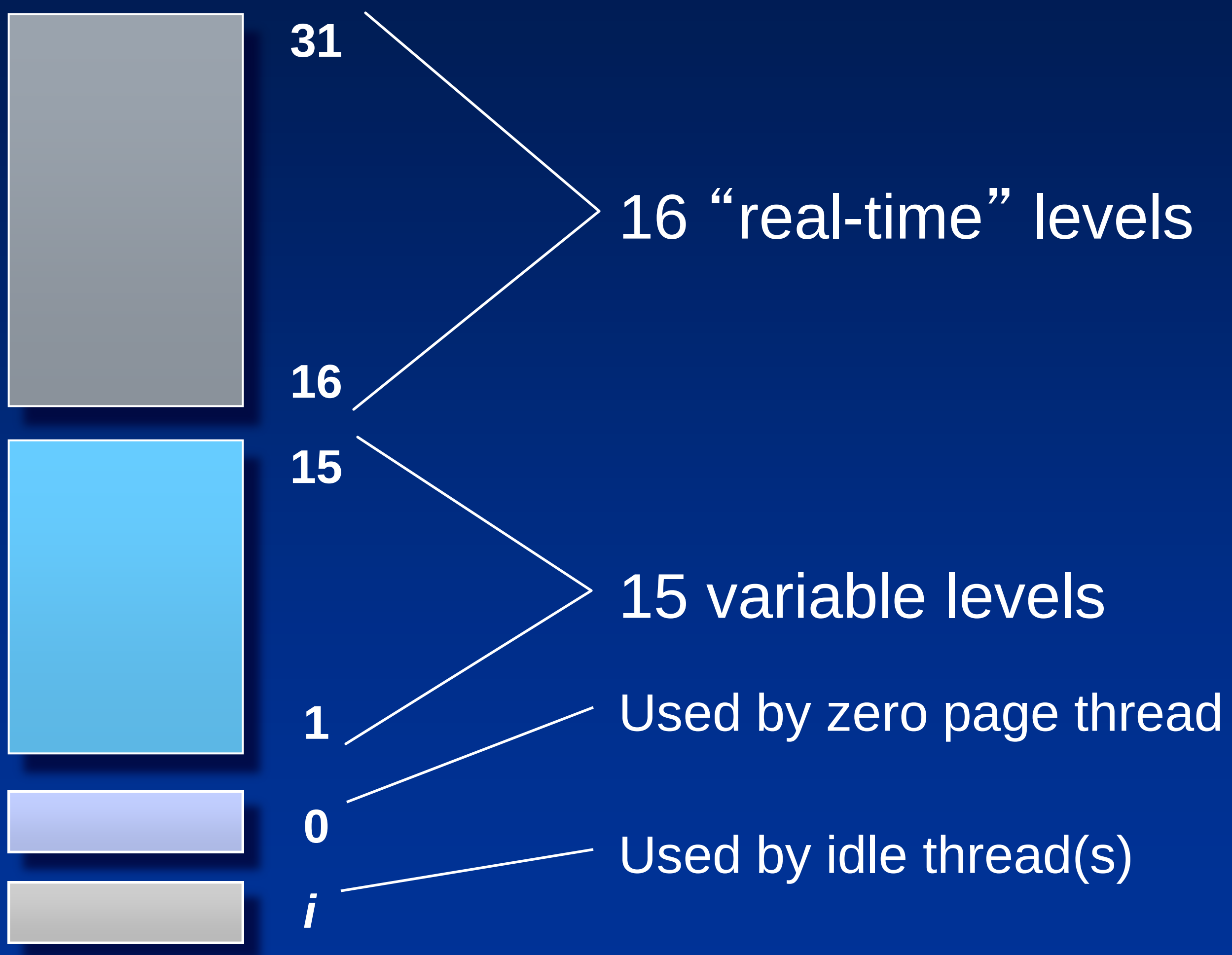
Overview of Scheduling

- Priority-driven, preemptive scheduling system
- Highest-priority runnable thread always runs
- Thread runs for time amount of *quantum*
- No single scheduler – event-based scheduling code spread across the kernel
- Dispatcher routines triggered by the following events:
  - Thread becomes ready for execution
  - Thread leaves running state (quantum expires, wait state)
  - Thread ‘s priority changes (system call/Windows change priority)
  - Processor affinity of a running thread changes
- Selecting a thread causes a *context switch*

Priority Levels

- 32 priority levels: 0 thru 31
- Threads within same priority are scheduled following the Round-Robin policy
- Non-Real-time Priorities (1-15) are adjusted dynamically – hence called “dynamic” range
  - Priority elevation as response to certain I/O and dispatch events
  - Quantum boosting to optimize responsiveness
- Real-time priorities (16-31) are assigned statically to threads

Thread Priority Levels



Scheduling

- Multiple threads may be ready to run
- "Who gets to use the CPU?"
- From Windows API point of view:
  - Processes are given a *priority class* upon creation
    - Idle, Below Normal, Normal, Above Normal, High, Real-time
  - Threads have a *relative priority* within the class
    - Idle, Lowest, Below_Normal, Normal, Above_Normal, Highest, and Time_Critical
    - Base priority: a function of priority class and relative priority
- From the kernel's view:
  - Threads have priorities 0 through 31
  - Threads are scheduled, not processes
  - Process priority class is not used to make scheduling decisions

Windows Scheduling-related APIs:

Get/SetPriorityClass
Get/SetThreadPriority
Get/SetProcessAffinityMask
SetThreadAffinityMask
SetThreadIdealProcessor
Suspend/ResumeThread

Mapping Win API Priority Levels to Kernel Priority Levels

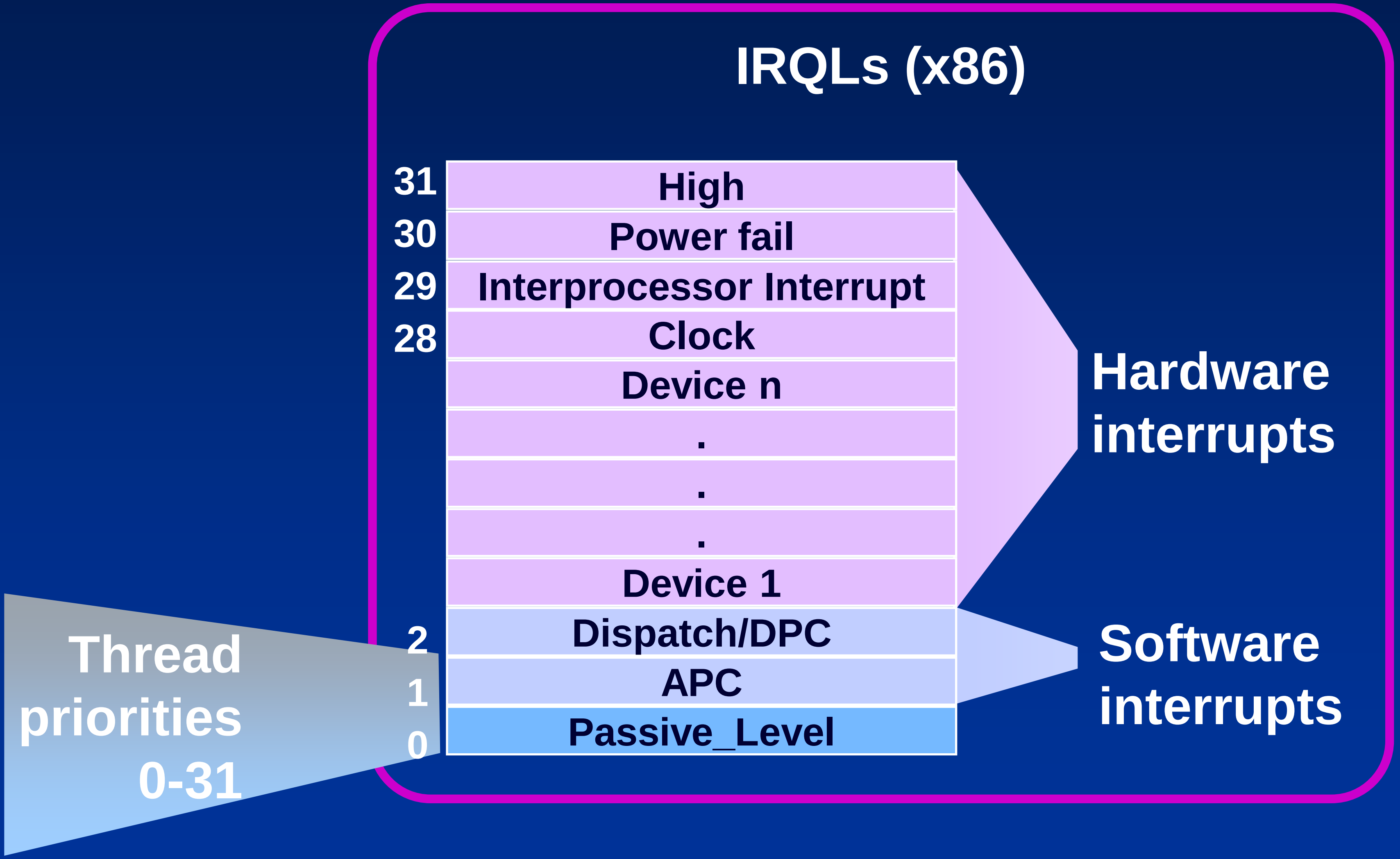
Thread Relative Priority	Process Priority Classes: Realtime	High	Above Normal	Normal	Below Normal	Idle
Time-critical	31	15	15	15	15	15
Highest	26	15	12	10	8	6
Above-normal	25	14	11	9	7	5
Normal	24	13	10	8	6	4
Below-normal	23	12	9	7	5	3
Lowest	22	11	8	6	4	2
Idle	16	1	1	1	1	1

- Table shows base priorities ("current" thread priority may be higher if base is < 15, since it's in the "dynamic range")
- Many utilities (such as Process Viewer) show the "current priority" of threads rather than the base (Performance Monitor can show both)
- Drivers can set to any value with *KeSetPriorityThread*
- Process base priority default to middle of priority range

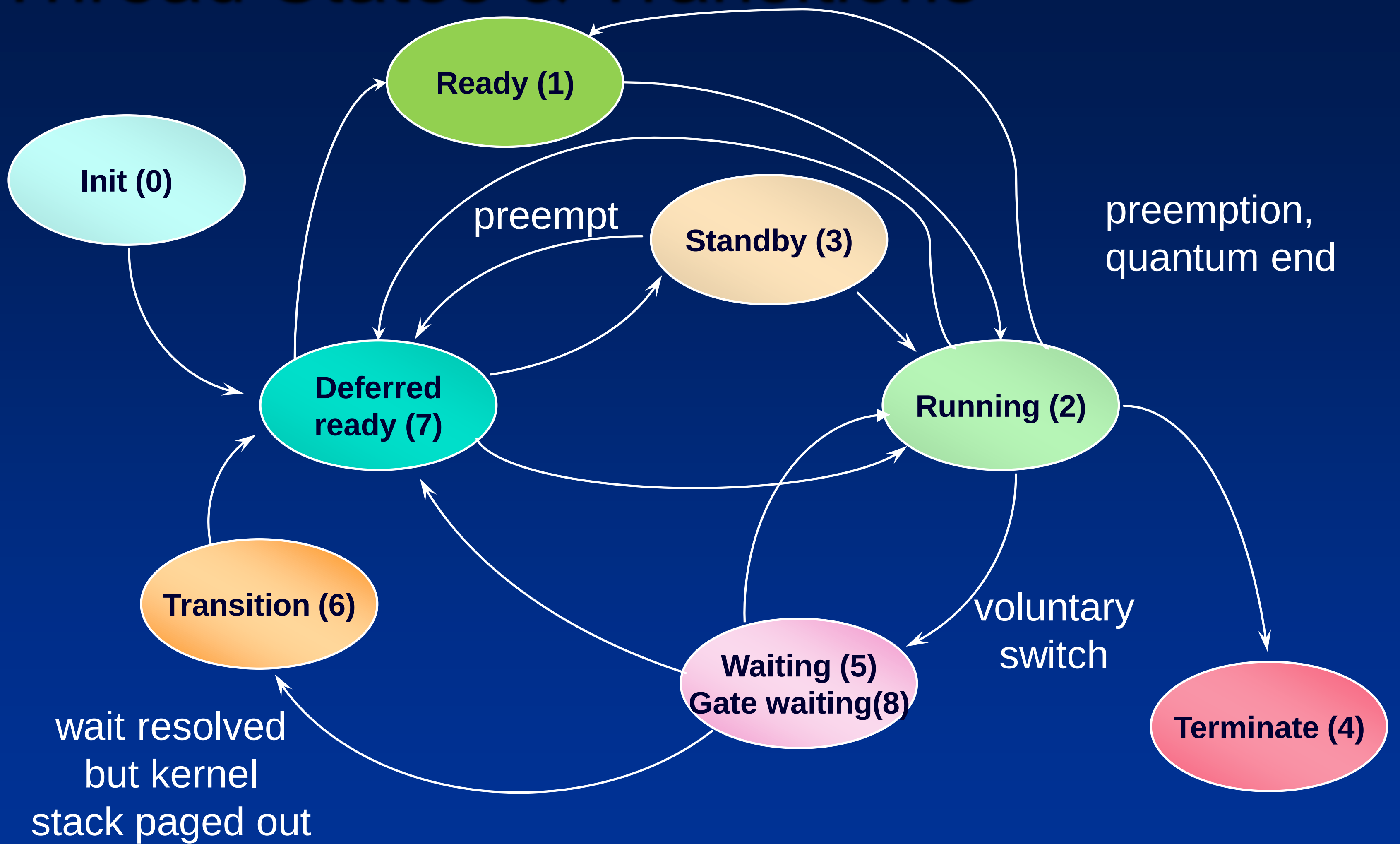
Special Thread Priorities

- Idle threads -- one per CPU
  - When no threads want to run, Idle thread "runs"
    - Not a real priority level - appears to have priority zero, but actually runs "below" priority 0, i.e., priority *i*
    - Provides CPU idle time accounting (unused clock ticks are charged to the idle thread)
  - Loop:
    - Calls HAL to allow for power management
    - Processes DPC list
    - Dispatches a thread if selected
    - in certain cases, scans per-CPU ready queues for next thread
- Zero page thread -- one per Windows system
  - *Zeroes* pages of memory in anticipation of "demand zero" page faults
  - Runs at priority zero (lower than any reachable from Windows)
  - Part of the "System" process (not a complete process)

Thread Scheduling Priorities vs. Interrupt Request Levels (IRQLs)



Thread States & Transitions



Ready = thread eligible to be scheduled to run
Deferred ready = thread selected to run but not scheduled
Standby = thread is selected to run on CPU (one per processor)

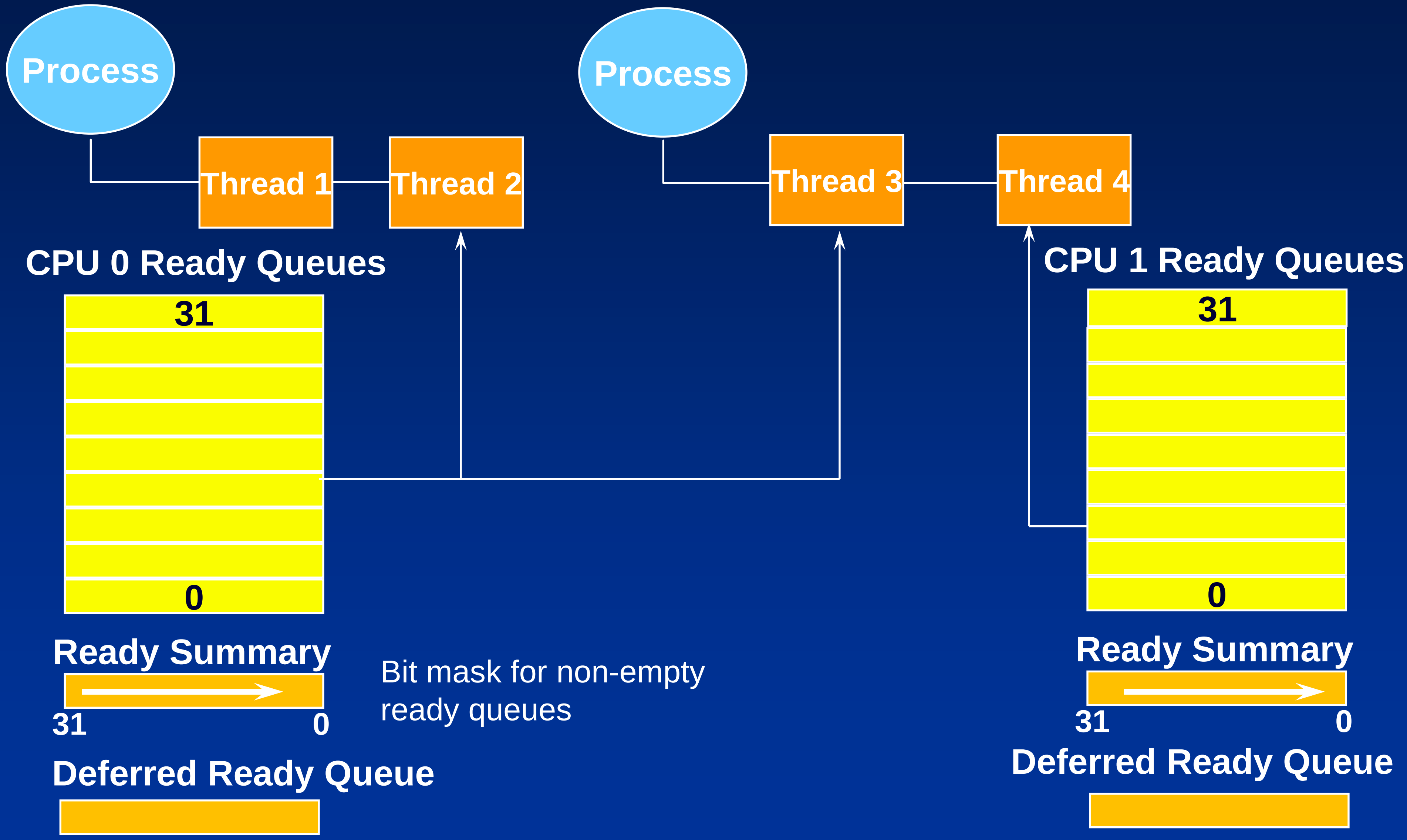
Thread Scheduling

- Priority driven, preemptive
  - 32 queues (FIFO lists) of "ready" threads
  - UP: highest priority thread always runs
  - MP: <u>One</u> of the highest priority runnable thread will be running somewhere
  - No attempt to share processor(s) "fairly" among processes, only among threads
    - Time-sliced, round-robin within a priority level
- Event-driven; no guaranteed execution period before preemption
  - When a thread becomes Ready, it either runs immediately or is inserted at the tail of the Ready queue for its current priority

Thread Scheduling

- No centralized scheduler!
  - i.e. there is no always-instantiated routine called "the scheduler"
  - The "code that does scheduling" is not a thread
  - Scheduling routines are simply called whenever events occur that change the Ready state of a thread
  - Things that cause scheduling events include:
    - interval timer interrupts (for quantum end)
    - interval timer interrupts (for timed wait completion)
    - other hardware interrupts (for I/O wait completion)
    - one thread changes the state of a waitable object upon which other thread(s) are waiting
    - a thread waits on one or more dispatcher objects
    - a thread priority is changed
- Kernel maintains *dispatcher database*
  - Threads waiting to execute
  - Which processors executing which threads

Dispatcher Database



Quantum Details

- Amount of time a thread gets to run before Windows checks for rescheduling
- Quantum internally stored as “3 * number of clock ticks”
  - Default quantum is 3 x 2 = 6 on Vista, 3 x 12 = 36 on Server
- Process and thread objects have a Quantum field
  - Process quantum is simply used to initialize thread quantum for all threads in the process
- Thread → Quantum field is decremented by 3 on every clock tick
- Quantum decremented by 1 when you come out of a wait
  - So that threads that get boosted after I/O completion won't keep running and never experiencing quantum end
  - Prevents I/O bound threads from getting unfair preference over CPU bound threads

Quantum Details

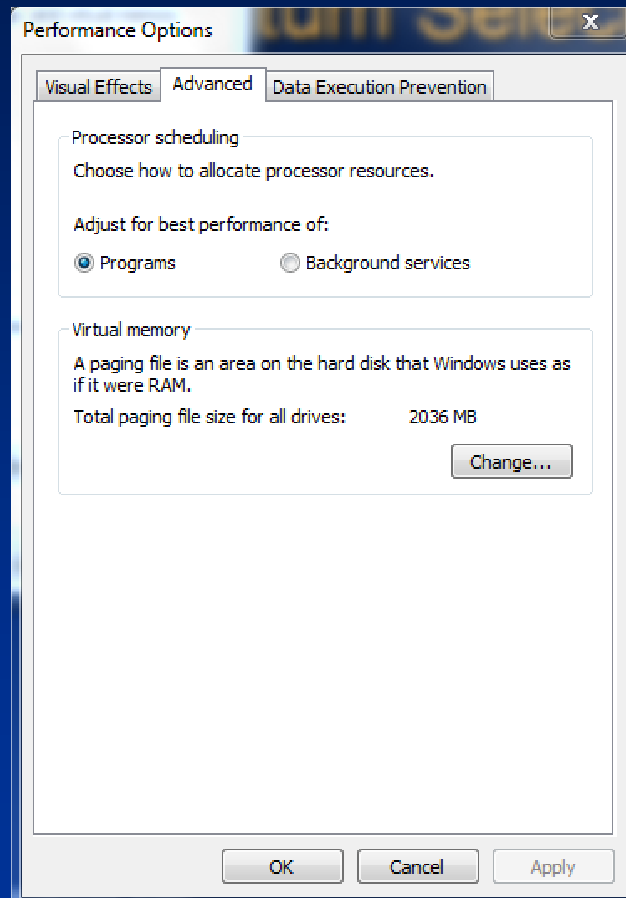
- When Thread→Quantum reaches zero (or less than zero):
  - you've experienced quantum end
  - waiting threads at same priority → *context switch*
  - Thread → Quantum = Process → Quantum; //restore quantum
  - for dynamic-priority threads, this is the only thing that restores the quantum
  - for real-time threads, quantum is also restored upon preemption
- Interval timer interrupts:
  - are not charged to the current thread's time

Quantum Boosting
(favoring foreground applications)

- Window brought into foreground
- All threads in the same process: quantum x 3, e.g. 6 clock ticks
- More responsiveness to foreground applications
- Quantum boosting does not happen on Server
  - Quantum on Server is always 12 ticks

Quantum Selection

- Windows can choose short or long quantums (e.g. for Terminal Servers)



Screen snapshot from:
System properties | Advanced | Performance settings | Advanced

Quantum Control

- Finer grained quantum control can be achieved by modifying
  HKLM\System\CurrentControlSet\Control
  \PriorityControl\Win32PrioritySeparation
  - 6 bit value

4	2	0
Short vs. Long	**Variable vs. Fixed**	**Quantum Boost**

- Short vs. Long

0,3	default (short for Vista, long for Server)
1	long
2	short

- Variable vs. Fixed

0,3	default (yes for Vista, no for Server)
1	yes
2	no

- Quantum Boost

0	fixed (overrides above setting)
1	double quantum of foreground threads
2,3	triple quantum of foreground threads

Controlling Quantum with Jobs

- If a process is a member of a job, quantum can be adjusted by setting the "Scheduling Class"
  - Only applies if process is higher than Idle priority class
  - Only applies if system running with fixed quantums (the default on Servers)
- Values are 0-9
  - 5 is default

Scheduling class	Quantum units
0	6
1	12
2	18
3	24
4	30
5	36
6	42
7	48
8	54
9	60

Scheduling Scenarios (I)

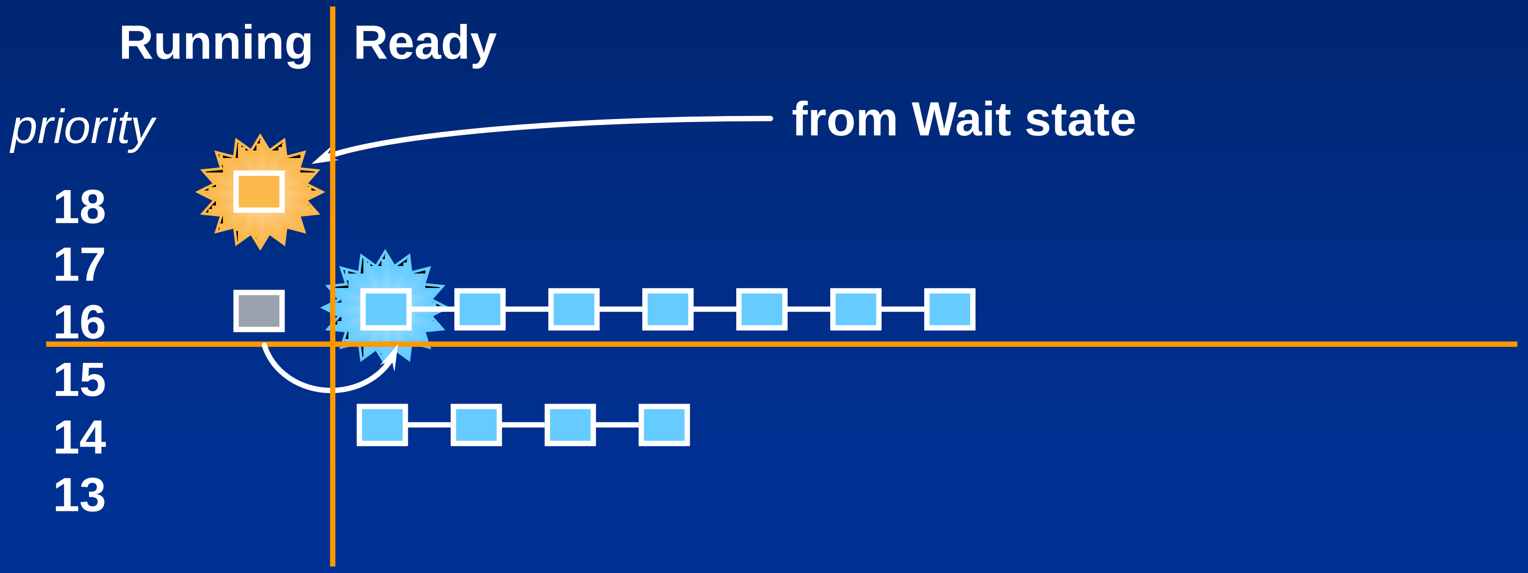
- Preemption
  - A thread becomes Ready at a higher priority than the running thread
  - Lower-priority Running thread is preempted
  - Preempted thread goes back to head of its Ready queue
    - action: pick lowest priority thread to preempt
- Voluntary switch
  - Waiting on a dispatcher object
  - Termination
  - Explicit lowering of priority
    - action: scan for next Ready thread (starting at your priority & down)

Scheduling Scenarios (II)

- Quantum end
  - Priority is decremented unless already at thread base priority
  - Thread goes to <u>tail</u> of ready queue for its new priority
  - May continue running if no equal or higher-priority threads are Ready
    - <u>action:</u> pick next thread at same priority level
- Termination
  - Thread finishes running: returned from main() or killed
  - Moves from running state to terminated state
  - No more handles on the thread object:
    - <u>action:</u> thread and assoc. structures de-allocated

Scheduling Scenarios
Preemption

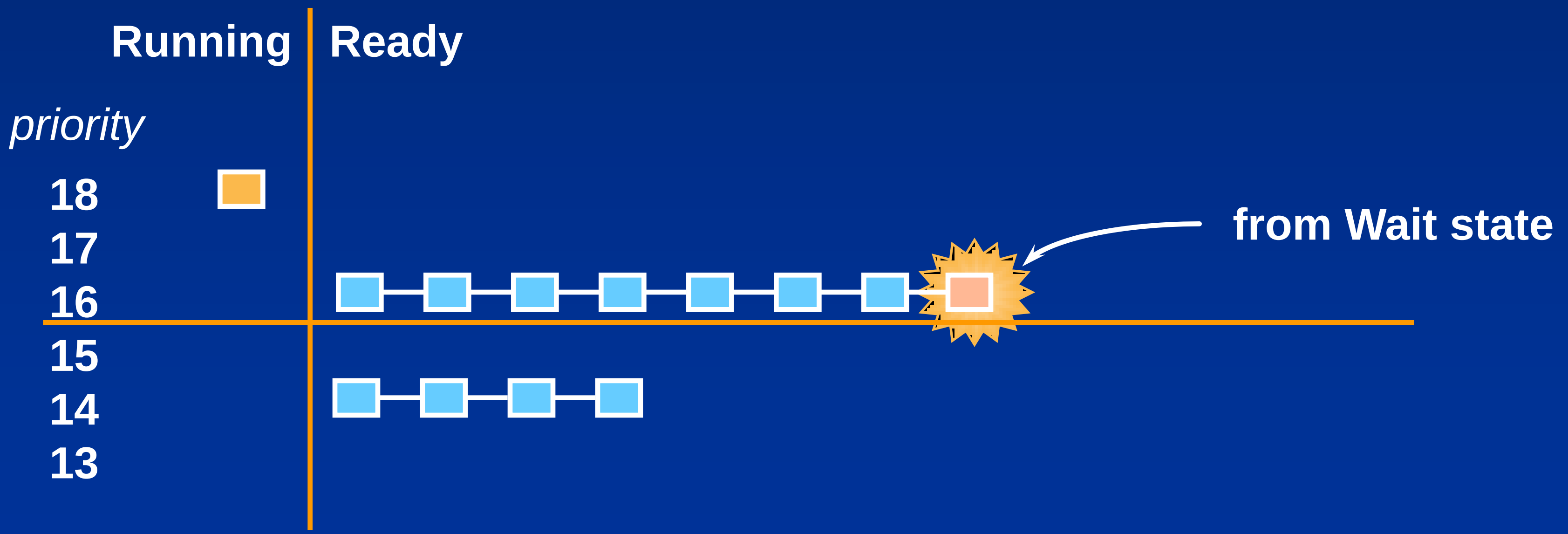
- Preemption is strictly event-driven
  - does not wait for the next clock tick
  - no guaranteed execution period before preemption
  - threads in kernel mode may be preempted (unless they raise IRQL to >= 2)



- A preempted thread goes back to the head of its ready queue

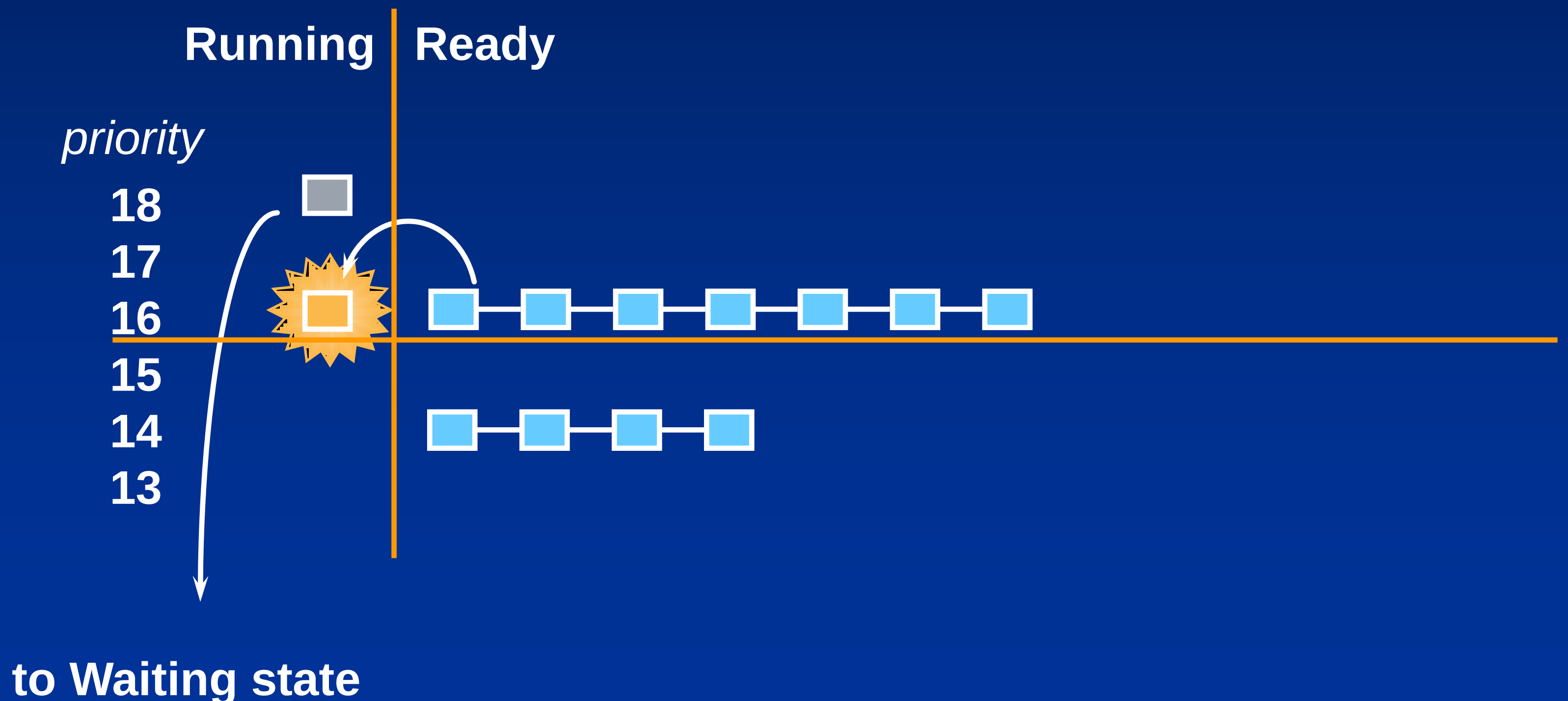
Scheduling Scenarios
Ready after Wait Resolution

- If newly-ready thread is not of higher priority than the running thread…
- …it is put at the tail of the ready queue for its current priority
  - If priority >=14 quantum is reset (t.b.d.)
  - If priority <14 and you're about to be boosted and didn't already have a boost, quantum is set to process quantum - 1



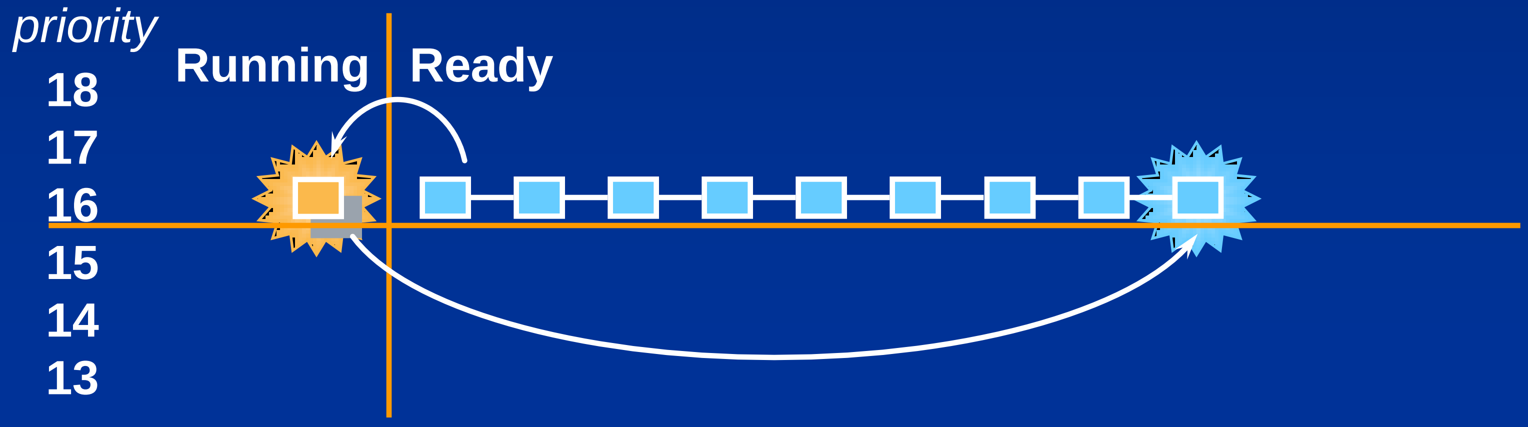
Scheduling Scenarios
Voluntary Switch

- When the running thread gives up the CPU…
- …Schedule the thread at the head of the next non-empty “ready” queue



Scheduling Scenarios
Quantum End

- When the running thread exhausts its CPU quantum, it goes to the end of its ready queue
  - Applies to both real-time and dynamic priority threads, user and kernel mode
    - Quantums can be disabled for a thread by a kernel function
  - Default quantum on Windows is 2 quantum units, 12 on Server
    - standard clock tick is 10 msec; might be 15 msec on some MP Pentium systems
  - if no other ready threads at that priority, same thread continues running (just gets new quantum)
  - if running at boosted priority, priority decays by one at quantum end (described later)



Priority Adjustments

- Dynamic priority adjustments (boost and decay) are applied to threads in "dynamic" classes
  - Threads with base priorities 1-15
  - Disable if desired with SetThreadPriorityBoost or SetProcessPriorityBoost
- Seven cases:
  - I/O completion
  - Wait completion on events or semaphores
  - When a thread has been waiting for an executive resource for too long
  - When threads in the foreground process complete a wait
  - When GUI threads wake up for windows input
  - For CPU starvation avoidance
  - Multimedia playback by Multimedia Class Scheduler Service (MMCSS)
- No automatic adjustments in "real-time" class (16 or above)
  - "Real time" here really means "system won't change the relative priorities of your real-time threads"
  - Hence, scheduling is predictable with respect to other "real-time" threads (but not for absolute latency)

Priority Boosting: After I/O Completion

To favor I/O intense threads:

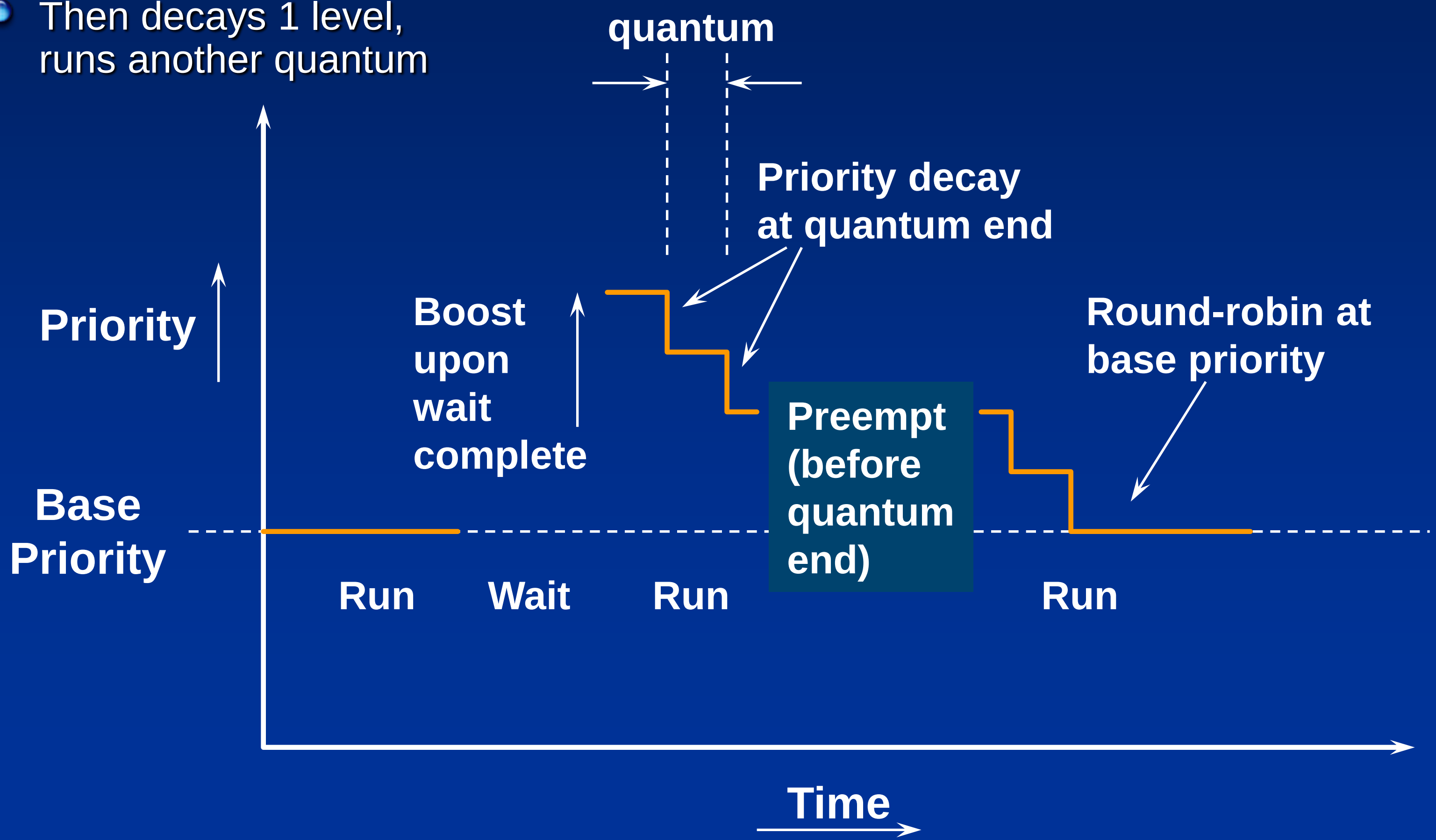
- After an I/O: specified by device driver
  - IoCompleteRequest(Irp, PriorityBoost)

Common boost values (see NTDDK.H)
1: disk, CD-ROM, parallel, Video
2: serial, network, named pipe, mailslot
6: keyboard or mouse
8: sound

- Applied to current priority (not base priority)
- After boost, run for one quantum
- Decays one priority level and continue until base priority level

Priority Boost and Decay

- Behavior of these boosts:
  - Applied to thread’s current priority
    - will not take you above priority 15
  - After a boost, you get one quantum
    - Then decays 1 level, runs another quantum



Priority Boosting: Waiting on Executive Resources

- Five second wait (to avoid deadlock)
- At the end of wait:
  - Acquire dispatcher lock
  - Boost owning thread
  - Wait again
- Boosting operation:
  - Applied to *base priority* (not current priority)
  - Raise priority to 14
  - Only applied if pri < waiting thread and < 14
  - Quantum reset : can run a full quantum

Priority Boosting: Foreground Threads after Wait

- *KiUnwaitThread* boost current priority by *PsPrioritySeparation*
- Improve responsiveness of interactive apps
- Applies to all windows systems
- Can’t disable this boost

Priority Boosting: CPU Starvation Avoidance

- **Balance Set Manager** system thread looks for "starved" threads
  - Balance set manager is a thread running at priority 16
  - Wakes up once per second and examines Ready queues
  - Looks for threads that have been Ready for 300 clock ticks (approximate 4 seconds on a 10ms clock)
  - Attempts to resolve "priority inversions" (see figure)
  - Priority is boosted to 15
  - Set quantum to 4
  - At quantum end, decays directly to base priority (no gradual decay) and normal quantum
  - Scans up to 16 Ready threads per priority level each pass
  - Boosts up to 10 Ready threads per pass
  - Like all priority boosts, does not apply in the real-time range (priority 16 and above)

Multiprocessor Scheduling

- Threads can run on any CPU, unless specified otherwise
  - Tries to keep threads on same CPU ("soft affinity")
  - Setting of which CPUs a thread will run on is called "hard affinity"
- Fully distributed (no "master processor")
  - Any processor can interrupt another processor to schedule a thread
- Dispatcher database:
  - Ready queues
  - Ready summary
  - Active processor mask: one bit for each usable processor
  - Idle summary: one bit for each idle processor

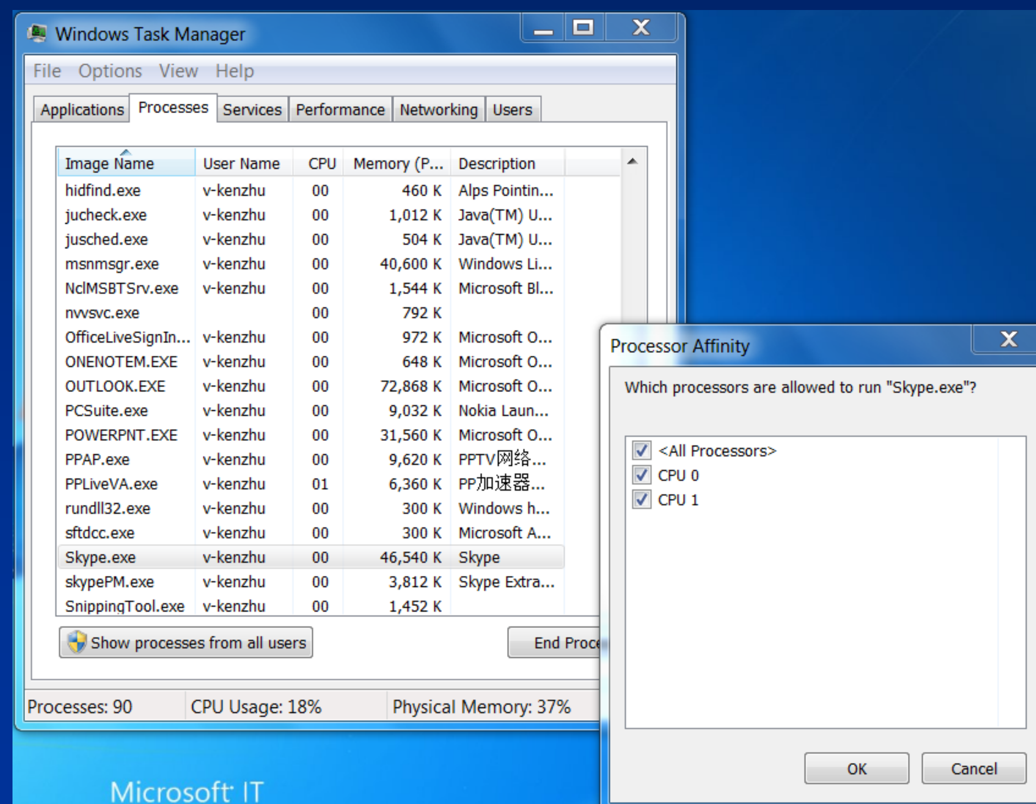
Multiprocessor Enhancements

- Threads always go into the ready queue of their ideal processor
- Instead of locking the dispatcher database to look for a candidate to run, per-CPU ready queue is checked first (first grabs PRCB spinlock) (PRCB = Processor Control Block)
  - If a thread has been selected to run on the CPU, does the context swap
  - Else begins scan of other CPU's ready queues looking for a thread to run
    - This scan is done OUTSIDE the dispatcher lock
    - Just acquires CPU PRCB lock
- Dispatcher lock still acquired to change system-wide state of a synchronization objects (mutexes, events and semaphores) and their waiting queues
- Bottom line: dispatcher lock is now held for a MUCH shorter time

Hard Affinity

- Affinity is a bit mask where each bit corresponds to a CPU number
  - Hard Affinity specifies where a thread is permitted to run
    - Defaults to all CPUs
  - Thread affinity mask must be subset of process affinity mask, which in turn must be a subset of the active processor mask

- Functions to change:
  - *SetThreadAffinityMask, SetProcessAffinityMask, SetInformationJobObject*
- Tools to change:
  - Task Manager or Process Explorer
    - Right click on process and choose “Set Affinity”
  - Psexec -a



Hard Affinity

- Can also set an image affinity mask during compilation
  - Search "Portable Executable and Common Object File Format Specification"
- Can also set "uniprocessor only" flag at compile time
  - sets affinity mask to one processor
  - System chooses 1 CPU for the process
    - Go round robin at each process creation
  - Useful as temporary workaround for multithreaded synchronization bugs that appear on MP systems
- NOTE: Setting hard affinity can lead to threads' getting less CPU time than they normally would
  - More applicable to large MP systems running dedicated server apps
  - Also, OS may in some cases run your thread on CPUs other than your hard affinity setting (flushing DPCs, setting system time)
    - Thread "system affinity" vs "user affinity"

Soft Processor Affinity

- Every thread has an “ideal processor”
  - System selects ideal processor for first thread in process (round robin across CPUs)
  - Next thread gets next CPU relative to the process seed
  - Can override with:

```
SetThreadIdealProcessor (
        HANDLE hThread,              // handle to the thread to be changed
        DWORD dwIdealProcessor);     // processor number
```

  - Hard affinity changes update ideal processor settings
  - Used in selecting where a thread runs next (see next slides)

  - For Hyperthreaded systems: first logical processor on the next physical processor
  - For NUMA systems: ideal node is chosen for a new process, ideal processor from ideal node assigned to the thread in this process

Choosing a CPU for a Ready Thread

- When a thread becomes ready to run (e.g. its wait completes, or it is just beginning execution), need to choose a processor for it to run on
- First, it sees if any processors are idle that are in the thread's hard affinity mask:
    - If its "ideal processor" is idle, it runs there
    - Else, if the previous processor it ran on is idle, it runs there
    - Else if the current processor is idle, it runs there
    - Else it picks the highest numbered idle processor in the thread's affinity mask
- If no processors are idle:
    - If the ideal processor is in the thread's affinity mask, it selects that
    - Else if the the last processor is in the thread's affinity mask, it selects that
    - Else it picks the highest numbered processor in the thread's affinity mask
- Finally, it compares the priority of the new thread with the priority of the thread running on the processor it selected (if any) to determine whether or not to perform a preemption

Selecting a Thread to Run on a CPU

- System needs to choose a thread to run on a specific CPU at:
  - At quantum end
  - When a thread enters a wait state
  - When a thread removes its current processor from its hard affinity mask
  - When a thread exits
- Starting with the first thread in the highest priority non-empty ready queue, it scans the queue for the first thread that has the current processor in its hard affinity mask and:
  - Ran last on the current processor, or
  - Has its ideal processor equal to the current processor, or
  - Has been in its Ready queue for 3 or more clock ticks, or
  - Has a priority >=24
- If it cannot find such a candidate, it selects the highest priority thread that can run on the current CPU (whose hard affinity includes the current CPU)
  - Note: this may mean going to a lower priority ready queue to find a candidate

Lab Demo

- Watching Foreground Priority Boosts and Decays
- “Listening” to MMCSS Priority Boosting

Lab: 2013-10-11

Lab

- Tchar.h
- Tlhelp32.h
- Traverse Processes (Simple & MSDN)
- How to Terminate a Process using PID

Tchar.h

- To simplify the transporting of code for international use, the Microsoft run-time library provides Microsoft-specific generic-text mappings for many data types, routines, and other objects. You can use these mappings, which are defined in Tchar.h, **to write generic code that can be compiled for single-byte, multibyte, or Unicode character sets**, depending on a manifest constant that you define by using a **#define** statement. Generic-text mappings are Microsoft extensions that are not ANSI compatible.

Tchar.h

- By using the Tchar.h, you can build single-byte, Multibyte Character Set (MBCS), and Unicode applications from the same sources. Tchar.h defines macros (which have the prefix **_tcs**) that, with the correct preprocessor definitions, map to **str**, **_mbs**, or **wcs** functions, as appropriate. To build MBCS, define the symbol **_MBCS**. To build Unicode, define the symbol **_UNICODE**. To build a single-byte application, define neither (the default). By default, **_MBCS** is defined for MFC applications.

Tlhelp32.h

- Tool Help Functions
  - Used for create tools for windows

ToolHelp Functions

Windows Mobile 6.5

A version of this page is also available for
Windows Embedded CE 6.0 R3
4/8/2010

The following table shows the ToolHelp functions with a description of the purpose of each.

Function	Description
CloseToolhelp32Snapshot	Closes a handle to a snapshot.
CreateToolhelp32Snapshot	Takes a snapshot of the processes, heaps, modules, and threads used by the processes.
Heap32First	Retrieves information about the first block of a heap allocated by a process.

Further Reading

- Mark E. Russinovich *et al*., Windows Internals, 5th Edition, Microsoft Press, 2009.
  - Chapter 5 - Processes, Thread, and Jobs (from pp. 391)
  - Thread Scheduling (from pp. 391)

Source Code References

- Windows Research Kernel sources
  - \base\ntos\ke\i386, \base\ntos\ke\amd64:
    - Ctxswap.asm – Context Swap
    - Clockint.asm – Clock Interrupt Handler
  - \base\ntos\ke
    - procobj.c - Process object
    - thredobj.c, thredsup.c – Thread object
    - Idsched.c – Idle scheduler
    - Wait.c – quantum management, wait resolution
    - Waitsup.c – dispatcher exit (deferred ready queue)
  - \base\ntos\inc\ke.h – structure/type definitions