Windows Kernel Internals
Thread Scheduling

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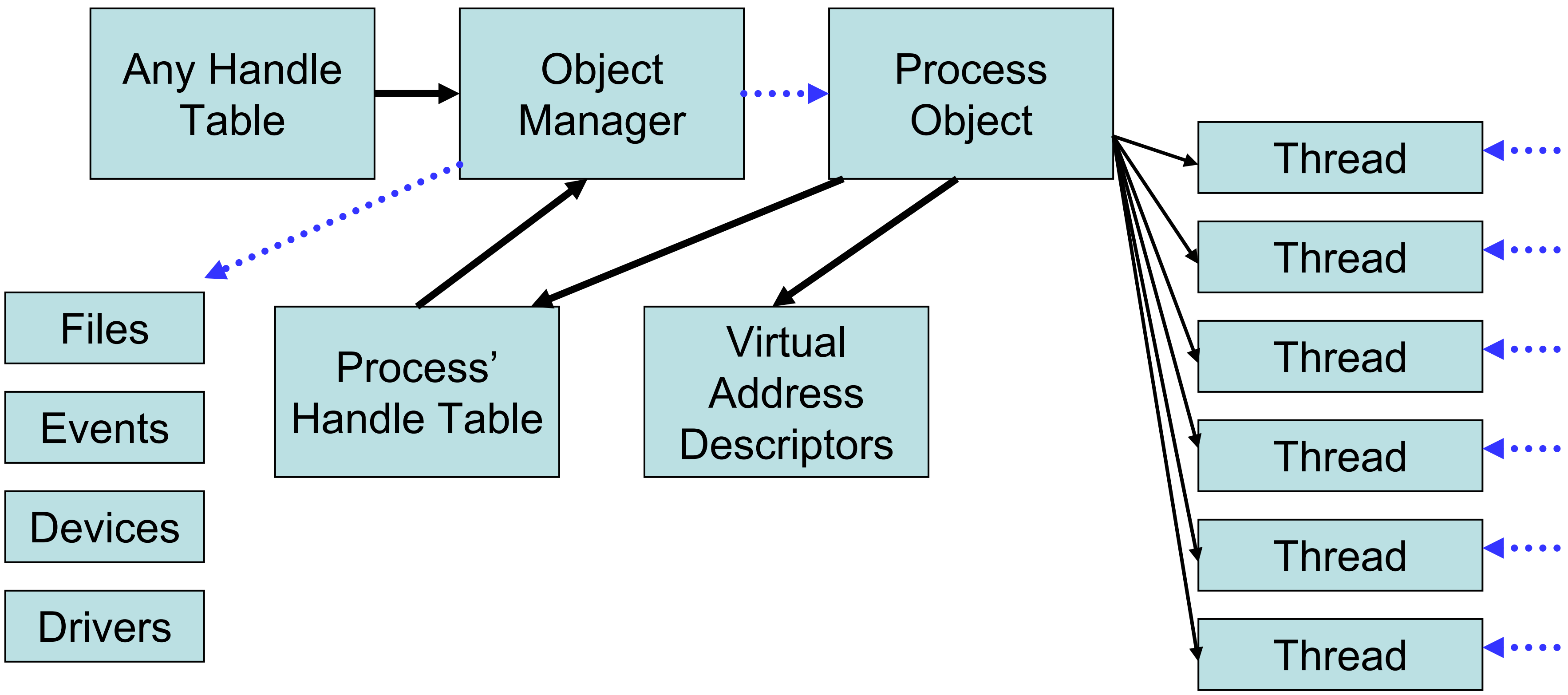
Process/Thread structure



Process

Container for an address space and threads

Associated User-mode Process Environment Block (PEB)

Primary Access Token

Quota, Debug port, Handle Table etc

Unique process ID

Queued to the Job, global process list and Session list

MM structures like the WorkingSet, VAD tree, AWE etc

Thread

- Fundamental schedulable entity in the system
- Represented by ETHREAD that includes a KTHREAD
- Queued to the process (both E and K thread)
- IRP list
- Impersonation Access Token
- Unique thread ID
- Associated User-mode Thread Environment Block (TEB)
- User-mode stack
- Kernel-mode stack
- Processor Control Block (in KTHREAD) for cpu state when not running

CPU Control-flow

Thread scheduling occurs at PASSIVE or APC level
  (IRQL < 2)

APCs (Asynchronous Procedure Calls) deliver I/O completions, thread/process termination, etc (IRQL == 1)
  Not a general mechanism like unix signals (user-mode code must explicitly block pending APC delivery)

Interrupt Service Routines run at IRL > 2

ISRs defer most processing to run at IRQL==2 (DISPATCH level) by queuing a DPC to their current processor

A pool of *worker threads* available for kernel components to run in a normal thread context when user-mode thread is unavailable or inappropriate

Normal thread scheduling is round-robin among priority levels, with priority adjustments (except for fixed priority real-time threads)

Asynchronous Procedure Calls

APCs execute routine in thread context

- not as general as UNIX signals
- user-mode APCs run when blocked & alertable
- kernel-mode APCs used extensively: timers, notifications, swapping stacks, debugging, set thread ctx, I/O completion, error reporting, creating & destroying processes & threads, …

APCs generally blocked in critical sections

- e.g. don’t want thread to exit holding resources

Deferred Procedure Calls

DPCs run a routine on a particular processor

- DPCs are higher priority than threads
- common usage is deferred interrupt processing
- ISR queues DPC to do bulk of work
  - *long DPCs harm perf, by blocking threads*
  - *Drivers must be careful to flush DPCs before unloading*
- also used by scheduler & timers (e.g. at quantum end)
- kernel-mode APCs used extensively: timers, notifications, swapping stacks, debugging, set thread ctx, I/O completion, error reporting, creating & destroying processes & threads, …

High-priority routines use IPI (inter-processor intr)

- used by MM to flush TLB in other processors

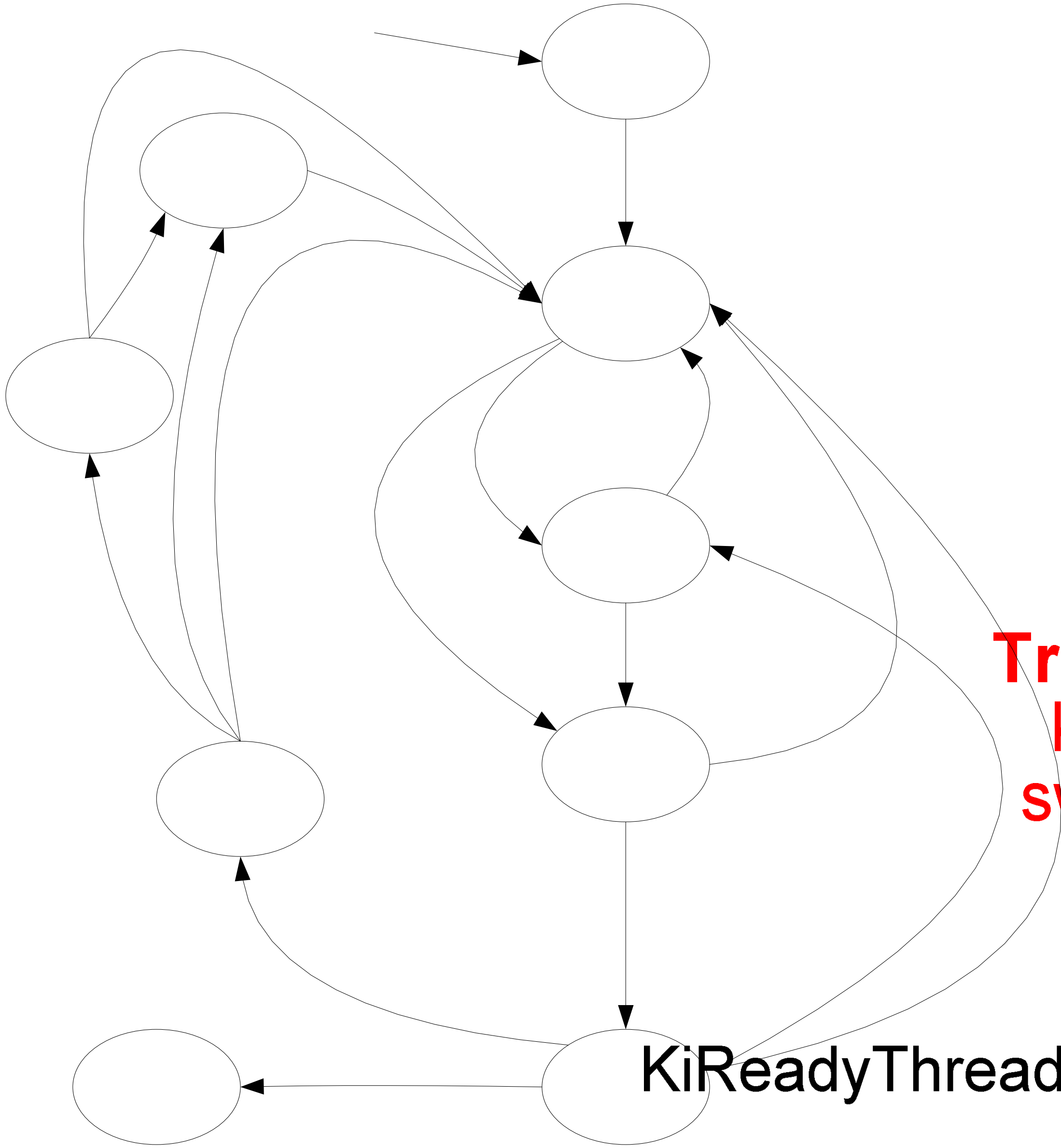
System Threads

- System threads have no user-mode context
  - Run in ‘system’ context, use system handle table
- System thread examples
  - Dedicated threads
    - Lazy writer, modified page writer, balance set manager, mapped pager writer, other housekeeping functions
  - General worker threads
    - Used to move work out of context of user thread
    - Must be freed before drivers unload
    - Sometimes used to avoid kernel stack overflows
  - Driver worker threads
    - Extends pool of worker threads for heavy hitters, like file server

Scheduling

- Windows schedules threads, not processes
  - Scheduling is preemptive, priority-based, and round-robin at the highest-priority
  - 16 real-time priorities above 16 normal priorities
  - Scheduler tries to keep a thread on its ideal processor/node to avoid perf degradation of cache/NUMA-memory
  - Threads can specify affinity mask to run only on certain processors
- Each thread has a current & base priority
  - Base priority initialized from process
  - Non-realtime threads have priority boost/decay from base
  - Boosts for GUI foreground, waking for event
  - Priority decays, particularly if thread is CPU bound (running at quantum end)
- Scheduler is state-driven by timer, setting thread priority, thread block/exit, etc
- Priority inversions can lead to starvation
  - balance manager periodically boosts non-running runnable threads

Thread scheduling states



Thread scheduling states

- Main quasi-states:
  - Ready – able to run
  - Running – current thread on a processor
  - Waiting – waiting an event
- For scalability Ready is three real states:
  - DeferredReady – queued on any processor
  - Standby – will be imminently start Running
  - Ready – queue on target processor by priority
- Goal is granular locking of thread priority queues
- Red states related to swapped stacks and processes

KPRCB Fields

Per-processor ready summary and ready queues

- WaitListHead[F/B]
- ReadySummary
- SelectNextLast
- DispatcherReadyListHeads[F/B][MAXIMUM_PRIORITY]
- pDeferredReadyListHead

Processor information

- VendorString[], InitialApicId, Hyperthreading, MHz, FeatureBits, CpuType, CpuID, CpuStep
- ProcessorNumber, Affinity SetMember
- ProcessorState, PowerState

KPRCB Fields - cont.

Miscellaneous counters

- InterruptCount, KernelTime, UserTime, DpcTime, DebugDpcTime, InterruptTime, Cc*Read*, KeExceptionDispatchCount, KeFloatingEmulationCount, KeSecondLevelTbFills, KeSystemCalls, ...

Per-processor pool lists and QueueLocks

- PP*LookasideList[], LockQueue[]

IPI and DPC related fields

- CurrentPacket, TargetSet, IPIWorkerRoutine, RequestSummary, SignalDone, …
- DpcData[], pDpcStack, DpcRoutineActive, ProcsGenericDPC, …

KTHREAD

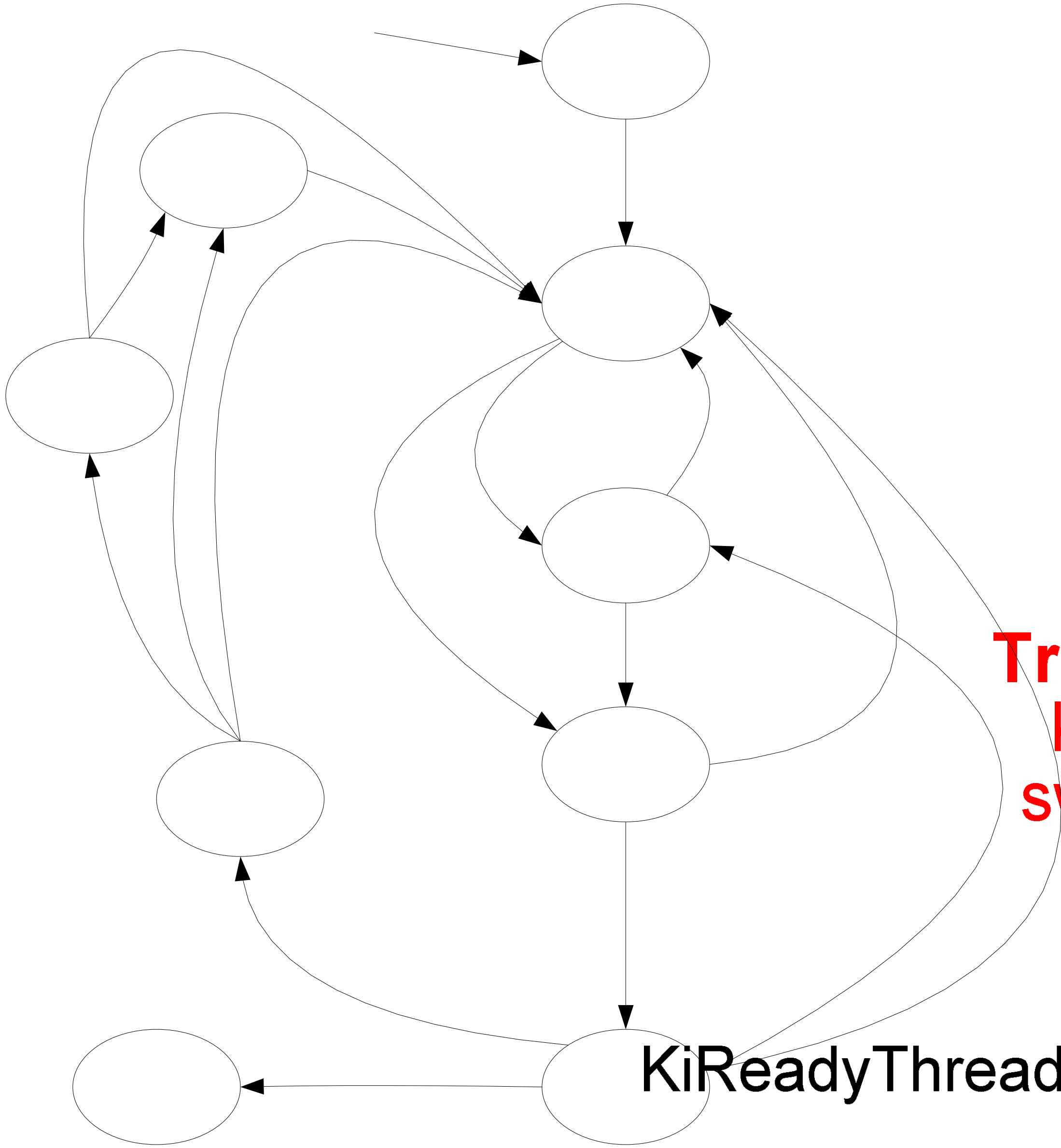
Scheduling-related fields

volatile UCHAR **State**;
volatile UCHAR **DeferredProcessor**;
SINGLE_LIST_ENTRY **SwapListEntry**;
LIST_ENTRY **WaitListEntry**;
SCHAR **Priority**;
BOOLEAN **Preempted**;
ULONG **WaitTime**;
volatile UCHAR **SwapBusy**;
KSPIN_LOCK **ThreadLock**;

APC-related fields

KAPC_STATE **ApcState**;
PKAPC_STATE **ApcStatePointer[2]**;
KAPC_STATE **SavedApcState**;
KSPIN_LOCK **ApcQueueLock**;

Thread scheduling states (yet again)



enum _KTHREAD_STATE

Ready	Queued on Prcb->DispatcherReadyListHead
Running	Pointed at by Prcb->CurrentThread
Standby	Pointed at by Prcb->NextThread
Terminated	
Waiting	Queued on WaitList->WaitBlock
Transition	Queued on KiStackInSwapList
Deferred Ready	Pointed at by Prcb->DeferredReadyListHead
Initialized	

Where states are set

Ready	Thread wakes up
Running	KeInitThread, KiIdleSchedule, KiSwapThread, KiExitDispatcher, NtYieldExecution
Standby	The thread selected to run next
Terminated	Set by KeTerminateThread()
Waiting	
Transition	Awaiting inswap by KiReadyThread()
Deferred…	
Initialized	Set by KeInitThread()

Idle processor preferences

(a) Select the thread's ideal processor – if idle, otherwise consider the set of all processors in the thread's hard affinity set

(b) If the thread has a preferred affinity set with an idle processor, consider only those processors

(c) If hyperthreaded and any physical processors in the set are completely idle, consider only those processors

(d) if this thread last ran on a member of this remaining set, select that processor, otherwise,

(e) if there are processors amongst the remainder which are not sleeping, reduce to that subset.

(f) select the leftmost processor from this set.

KiInsertDeferredReadyList ()

Prcb = KeGetCurrentPrcb();

Thread->State = DeferredReady;

Thread->DeferredProcessor = Prcb->Number;

PushEntryList(&Prcb->DeferredReadyListHead, &Thread->SwapListEntry);

KiDeferredReadyThread()

// assign to idle processor or preempt a lower-pri thread
if boost requested, adjust pri under threadlock
if there are idle processors, pick processor
    acquire PRCB locks for us and target processor
    set thread as Standby on target processor
    request dispatch interrupt of target processor
    release both PRCB locks
    return

KiDeferredReadyThread() - cont

target is the ideal processor
acquire PRCB locks for us and target
if (victim = target->NextThread)
    if (thread->Priority <= victim->Priority)
        insert thread on Ready list of target processor
        release both PRCB locks and return
        victim->Preempted = TRUE
    set thread as Standby on target processor
    set victim as DeferredReady on our processor
    release both PRCB locks
    target will pickup thread instead of victim
    return

KiDeferredReadyThread() – cont2

victim = target->CurrentThread

acquire PRCB locks for us and target

if (thread->Priority <= victim->Priority)

    insert thread on Ready list of target processor

    release both PRCB locks and return

victim->Preempted = TRUE

set thread as Standby on target processor

release both PRCB locks

request dispatch interrupt of target processor

return

KiInSwapProcesses()

// Called from only:

KeSwapProcessOrStack [System Thread]

For every process in swap-in list

Sets ProcessInSwap

Calls MmInSwapProcess

Sets ProcessInMemory

KiQuantumEnd()

```
// Called at dispatch level
Raise to SYNCH level, acquire ThreadLock, PRCB Lock
if thread->Quantum <= 0
    thread->Quantum = Process->ThreadQuantum
    pri = thread->Priority = KiComputeNewPriority(thread)
    if (Prcb->NextThread == NULL)
        newThread = KiSelectReadyThread (pri, Prcb)
        if (newThread)
            newThread->State = Standby
            Prcb->NextThread = newThread
    else thread->Preempted = FALSE
```

KiQuantumEnd() – cont.

release the ThreadLock

if (! Prcb->NextThread) release PrcbLock, return

thread->SwapBusy = TRUE

newThread = Prcb->NextThread

Prcb->NextThread = NULL

Prcb->CurrentThread = newThread

newThread->State = **Running**

thread->WaitReason = WrQuantumEnd

KxQueueReadyThread(thread, Prcb)

thread->WaitIrql = APC_LEVEL

KiSwapContext(thread, newThread)

KxQueueReadyThread(Thread, Prcb)

```
if ((Thread->Affinity & Prcb->SetMember) != 0)
    Thread->State = Ready
    pri = Thread->Priority
    Preempted = Thread->Preempted;
    Thread->Preempted = 0
    Thread->WaitTime = KiQueryLowTickCount()
    insertfcn = Preempted? InsertHeadList : InsertTailList
    Insertfcn(&Prcb->ReadyList [PRI],
                                    &Thread->WaitListEntry)
    Prcb->ReadySummary |= PRIORITY_MASK(PRI)
    KiReleasePrcbLock(Prcb)
```

KxQueueReadyThread … cont.

else

    Thread->State = DeferredReady

    Thread->DeferredProcessor = Prcb->Number

    KiReleasePrcbLock(Prcb)

    KiDeferredReadyThread(Thread)

KiExitDispatcher(oldIrql)

```
// Called at SYNCH_LEVEL
Prcb = KeGetCurrentPrcb()
if (Prcb->DeferredReadyListHead.Next)
    KiProcessDeferredReadyList(Prcb)
if (oldIrql >= DISPATCH_LEVEL)
    if (Prcb->NextThread && !Prcb->DpcRoutineActive)
        KiRequestSoftwareInterrupt(DISPATCH_LEVEL)
    KeLowerIrql(oldIrql)
    return
// oldIrql < DISPATCH_LEVEL
KiAcquirePrcbLock(Prcb)
```

KiExitDispatcher(oldIrql) – cont.

```
NewThread = Prcb->NextThread
CurrentThread = Prcb->CurrentThread
thread->SwapBusy = TRUE
Prcb->NextThread = NULL
Prcb->CurrentThread = NewThread
NewThread->State = Running
KxQueueReadyThread(CurrentThread, Prcb)
CurrentThread->WaitIrql = OldIrql
Pending = KiSwapContext(CurrentThread, NewThread)
if (Pending != FALSE)
    KeLowerIrql(APC_LEVEL);
    KiDeliverApc(KernelMode, NULL, NULL);
```

Kernel Thread Attach

Allows a thread in the kernel to temporarily move to a different process' address space

- Used heavily in VM system
- Used by object manager for kernel handles
- PspProcessDelete attaches before calling ObKillProcess() so close/delete in process context
- Used to query a process' VM counters

KiAttachProcess (Thread, Process, APCLock, SavedApcState)

```
Process->StackCount++
KiMoveApcState(&Thread->ApcState, SavedApcState)
Re-initialize Thread->ApcState
if (SavedApcState == &Thread->SavedApcState)
    Thread->ApcStatePointer[0] = &Thread->SavedApcState
    Thread->ApcStatePointer[1] = &Thread->ApcState
    Thread->ApcStateIndex = 1
// assume ProcessInMemory case and empty ReadyList
Thread->ApcState.Process = Process
KiUnlockDispatcherDatabaseFromSynchLevel()
KeReleaseInStackQueuedSpinLockFromDpcLevel(APCLock)
KiSwapProcess(Process, SavedApcState->Process)
KiExitDispatcher(LockHandle->OldIrql)
```

Asynchronous Procedure Calls

APCs execute code in context of a particular thread

APCs run only at PASSIVE or APC LEVEL (0 or 1)

Three kinds of APCs

- **User-mode:** deliver notifications, such as I/O done
- **Kernel-mode:** perform O/S work in context of a process/thread, such as completing IRPs
- **Special kernel-mode:** used for process termination

Multiple ‘environments’:

- **Original:** The normal process for the thread (ApcState[0])
- **Attached:** The thread as attached (ApcState[1])
- **Current:** The ApcState[ ] as specified by the thread
- **Insert:** The ApcState[ ] as specified by the KAPC block

KAPC

pThread			
ApcListEntry[2]			
pKernelRoutine			
pRundownRoutine			
pNormalRoutine			
pNormalContext			
SystemArguments[2]			
	Inserted	Mode	ApcStateIdx

KeInitializeApc()

```
// assume CurrentApcEnvironment case
Apc->ApcStateIndex = Thread->ApcStateIndex
Apc->Thread = Thread;
Apc->KernelRoutine = KernelRoutine
Apc->RundownRoutine = RundownRoutine      // optional
Apc->NormalRoutine = NormalRoutine        // optional
if NormalRoutine
    Apc->ApcMode = ApcMode                // user or kernel
    Apc->NormalContext = NormalContext
else  // Special kernel APC
    Apc->ApcMode = KernelMode
    Apc->NormalContext = NIL
Apc->Inserted = FALSE
```

KiInsertQueueApc()

Insert the APC object in the APC queue for specified mode

- **Special APCs (! Normal) – insert after other specials**
- **User APC && KernelRoutine is PsExitSpecialApc() – set UserAPCPending and insert at front of queue**
- **Other APCs – insert at back of queue**

For kernel-mode APC

if thread is Running: KiRequestApcInterrupt(processor)

if Waiting at PASSIVE &&

(special APC && !Thread->SpecialAPCDisable ||

kernel APC && !Thread->KernelAPCDisable) call KiUnwaitThread(thread)

If user-mode APC && threads in alertable user-mode wait

set UserAPCPending and call KiUnwaitThread(thread)

KiDeliverApc()

Called at APC level from the APC interrupt code

and at system exit (when either APC pending flag is set)

- All special kernel APC's are delivered first
- Then normal kernel APC's (unless one in progress)

Finally

- if the user APC queue is not empty
- && Thread->UserAPCPending is set
- && previous mode is user

Then a user APC is delivered

Scheduling Summary

- Scheduler lock broken up per-processor
  - Achieves high-scalability for otherwise hot lock
- Scheduling is preemptive by higher priority threads, but otherwise round-robin
- Boosting is used for non-realtime threads
- Threads are swapped out by balance set manager to reclaim memory (stack)
- Balance Set Manager manages residence, drives workingset trims, and fixes deadlocks

Discussion