Real-Time Programming & RTOS

Concurrent and real-time programming tools

Concurrent Programming

Concurrency in real-time systems

- typical architecture of embedded real-time system:
  - several input units
  - computation
  - output units
  - data logging/storing
- i.e., handling several concurrent activities
- concurrency occurs naturally in real-time systems

Support for concurrency in programming languages (Java, Ada, ...)
advantages: readability, OS independence, checking of interactions by compiler, embedded computer may not have an OS

Support by libraries and the operating system (C/C++ with POSIX)
advantages: multi-language composition, language's model of concurrency may be difficult to implement on top of OS, OS API stadards imply portability

Processes and Threads

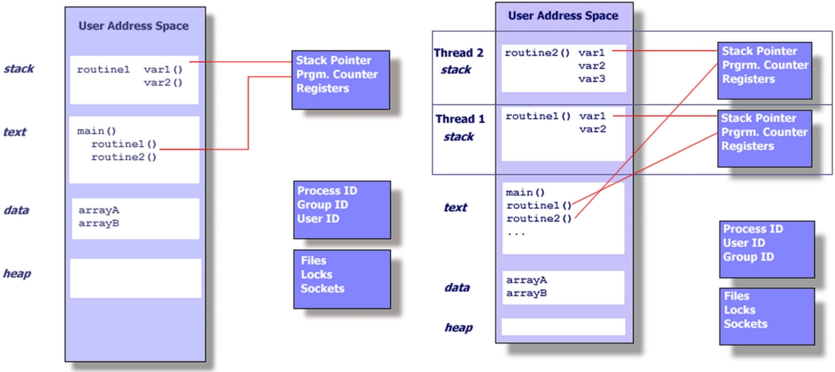
Process

- running instance of a program,
- executes its own virtual machine to avoid interference from other processes,
- contains information about program resources and execution state, e.g.:
  - environment, working directory, ...
  - program instructions,
  - registers, heap, stack,
  - file descriptors,
  - signal actions, inter-process communication tools (pipes, message boxes, etc.)

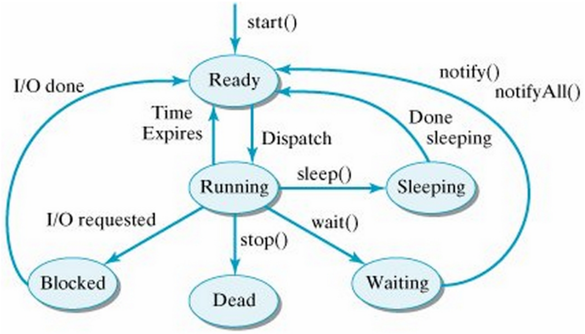
Thread

- exists *within a process*, uses process resources ,
- can be scheduled by OS and run as an independent entity,
- keeps its own: execution stack, local data, etc.
- share global data and resources with other threads of the same process

Processes and threads in UNIX



Process (Thread) States



Communication and Synchronization

Communication

- passing of information from one process (thread) to another
- typical methods: shared variables, message passing

Synchronization

- satisfaction of constraints on the interleaving of actions of processes

  e.g. action of one process has to occur after an action of another one
- typical methods: semaphores, monitors

Communication and synchronization are linked:

- communication requires synchronization
- synchronization corresponds to communication without content

Communication: Shared Variables

Consistency problems:

- unrestricted use of shared variables is unreliable
- *multiple update problem*

  example: shared variable X, assignment $X := X + 1$

  - load the current value of X into a register
  - increment the value of the register
  - store the value of the register back to X
- two processes executing these instruction $\Rightarrow$ certain interleavings can produce inconsistent results

Solution:

- parts of the process that access shared variables (i.e. critical sections) must be executed indivisibly with respect to each other
- required protection is called *mutual exclusion*

... one may use a special mutual ex. protocol (e.g. Peterson) or a synchronization mechanism – semaphores, monitors

Synchronization: Semaphores

A sempahore contains an integer variable that, apart from initialization, is accessed only through two standard operations: `wait()` and `signal()`.

- semaphore is initialized to a non-negative value (typically 1)
- `wait()` operation: decrements the semaphore value if the value is positive; otherwise, if the value is zero, the caller becomes blocked
- `signal()` operation: increments the semaphore value; if the value is not positive, then one process blocked by the semaphore is unblocked (usually in FIFO order)
- both `wait` and `signal` are atomic

Semaphores are elegant low-level primitive but error prone and hard to debug (deadlock, missing signal, etc.)

For more details see an operating systems course.

Synchronization: Monitors

- *encapsulation* and efficient condition synchronization
- critical regions are written as procedures; all encapsulated in a single object or module
- procedure calls into the module are guaranteed to be mutually exclusive
- shared resources accessible only by these procedures

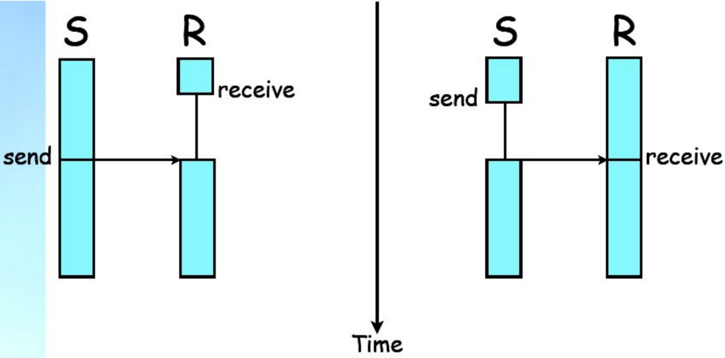
For more details (such as condition variables) see an operating systems course.

Communication: Message Passing

Communication among two, or more processes where there is no shared region between the two processes. Instead they communicate by passing messages.

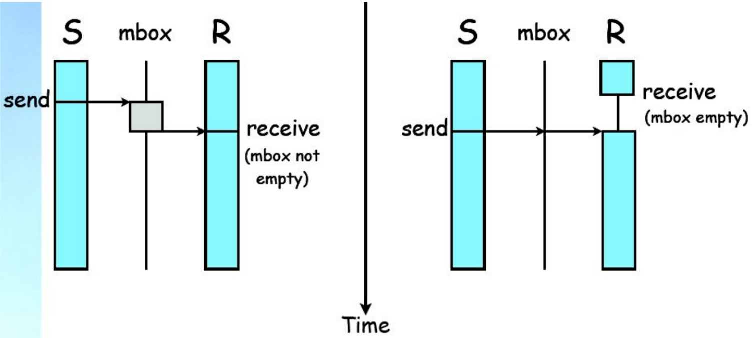
- **synchronous** (rendezvous): send and receive operations are blocking, no buffer required
- **asynchronous** (no-wait): send operation is not blocking, requires buffer space (mailbox)
- **remote invocation** (extended rendezvous): sender is blocked until reply is received

Synchronous Message Passing



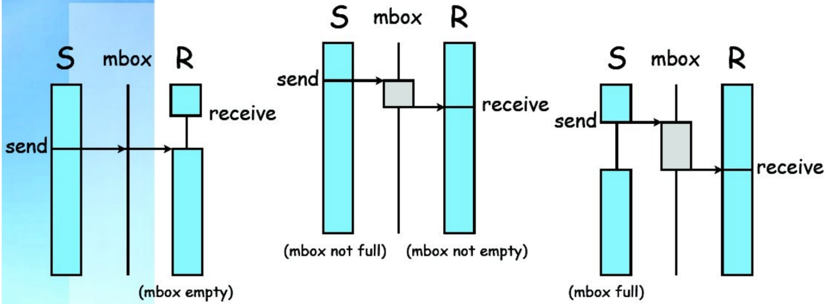
Both send and receive may block indefinitely!

Asynchronous Message Passing



Only the receiver might block indefinitely!

Asynch. Message Passing with Bounded Buffer



Receiver blocks if mbox is empty,
sender blocks if mbox is full

Note: size = 0 gives synchronous communication!

Concurrent Programming is Complicated

Multi-threaded applications with **shared data** may have numerous flaws.

- **Race condition**

  Two or more threads try to access the same shared data, the result depends on the exact order in which their instructions are executed
- **Deadlock**

  occurs when two or more threads wait for each other, forming a cycle and preventing all of them from making any forward progress
- **Starvation**

  an idefinite delay or permanent blocking of one or more runnable threads in a multithreaded application
- **Livelock**

  occurs when threads are scheduled but are not making forward progress because they are continuously reacting to each other's state changes

Usually difficult to find bugs and verify correctness.

Real-Time Aspects

- **time-aware systems** make explicit references to the time frame of the enclosing environment

  e.g. a bank safe's door are to be locked from midnight to nine o'clock

  - the "real-time" of the environment must be available
- **reactive systems** are typically concerned with relative times

  an output has to be produced within 50 ms of an associated input

  - must be able to measure intervals
  - usually must synchronize with environment: input sampling and output signalling must be done very regularly with controlled variability

The Concept of Time

Real-time systems must have a concept of time – but what is time?

- Measure of a time interval
  - Units?

    seconds, milliseconds, cpu cycles, system "ticks"
  - Granularity, accuracy, stability of the clock source
    - Is "one second" a well defined measure?

      "A second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom."
    - ... temperature dependencies and relativistic effects

      (the above definition refers to a caesium atom at rest, at mean sea level and at a temperature of 0 K)
  - Skew and divergence among multiple clocks

    Distributed systems and clock synchronization
- Measuring time
  - external source (GPS, NTP, etc.)
  - internal – hardware clocks that count the number of oscillations that occur in a quartz crystal

Requirements for Interaction with "time"

For RT programming, it is desirable to have:

- access to clocks and representation of time
- delays
- timeouts
- (deadline specification and real-time scheduling)

Access to Clock and Representation of Time

- requires a hardware clock that can be read like a regular external device
- mostly offered by an OS service, if direct interfacing to the hardware is not allowed

Example of time representation: (POSIX high resolution clock, counting seconds and nanoseconds since 1970 with known resolution)

```
struct timespec {
    time_t tv_sec;
    long   tv_nsec;
}

int clock_gettime( clockid_t clock_id,
                   struct timespec * tp );
int clock_settime( clockid_t id,
                   const struct timespec * tp );
```

Time is often kept by incrementing an integer variable, need to take case of overflows (i.e. jumps to the past).

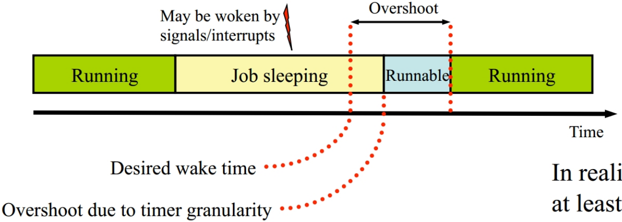
Delays

In addition to having access to a clock, need ability to

- Delay execution until an arbitrary calendar time

  What about daylight saving time changes? Problems with leap seconds.

- Delay execution for a relative period of time
  - Delay for *t* seconds



In reality: delay at least *t* seconds

  - Delay for *t* seconds after event *e* begins

```
start = curr_time();
do_action1();
delay(10.0 - (curr_time() - start));
do_action2();
```

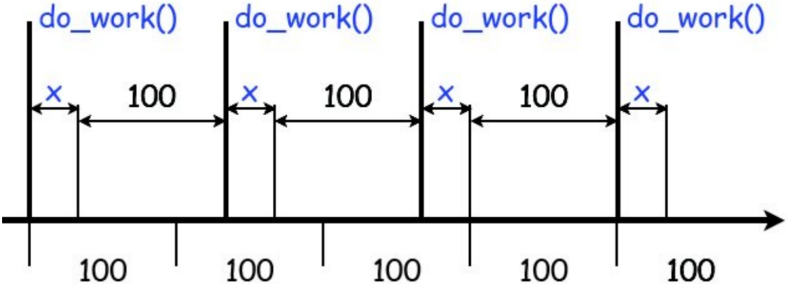
What if pre-empted between these?
Oversleep unless system has a function
`delay_until(start+10.0)`

A Repeated Task (An Attempt)

The goal is to `do work` repeatedly every 100 time units

```
while(1) {
  delay(100);
  do_work();
}
```

Does it work as intended? No, accumulates drift ...



Each turn in the loop will take at least 100 + x milliseconds, where x is the time taken to perform `do_work()`

A Repeated Task (An Attempt)

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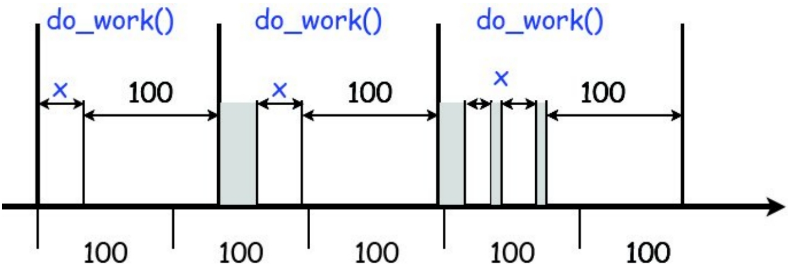


Delay is just lower bound, a delaying process is not guaranteed access to the processor (the delay does not compensate for this)

Eliminating (Part of) The Drift: Timers

- Set an alarm clock, do some work, and then wait for whatever time is left before the alarm rings
- This is done with timers
- Thread is told to wait until the next ring – accumulating drift is eliminated
- Two types of timers
  - one-shot
    After a specified interval call an associated function.
  - periodic (also called auto-reload timer in freeRTOS)
    Call the associated function repeatedly, always after the specified interval.
- Even with timers, drift may still occur, but it does not accumulate (local drift)

Timeouts

Synchronous blocking operations can include timeouts

- Synchronization primitives

  Semaphores, locks, etc.

  ... timeout usually generates an error/exception

- Networking and other I/O calls

  E.g. `select()` in POSIX

  Monitors readiness of multiple file descriptors, is ready when the corresponding operation with the file desc is possible without blocking. Has a timeout argument that specifies the minimum interval that `select()` should block waiting for a file descriptor to become ready.

May also provide an asynchronous timeout signal

- Detect time overruns during execution of periodic and sporadic tasks

Deadline specification and real-time scheduling

Clock driven scheduling trivial to implement via cyclic executive.

Other scheduling algorithms need OS and/or language support:

- System calls create, destroy, suspend and resume tasks.
- Implement tasks as either threads or processes.

  Threads usually more beneficial than processes (with separate address space and memory protection):
  - Processes not always supported by the hardware
  - Processes have longer context switch time
  - Threads can communicate using shared data (fast and more predictable)
- Scheduling support:
  - Preemptive scheduler with multiple priority levels
  - Support for aperiodic tasks (at least background scheduling)
  - Support for sporadic tasks with acceptance tests, etc.

Jobs, Tasks and Threads

- In theory, a system comprises a set of (abstract) *tasks*, each task is a series of *jobs*
  - tasks are typed, have various parameters, react to events, etc.
  - Acceptance test performed before admitting new tasks
- In practice, a *thread* (or a process) is the basic unit of work handled by the scheduler
  - Threads are the instantiation of tasks that have been admitted to the system

How to map *tasks* to *threads*?

Periodic Tasks

Real-time tasks defined to execute periodically $T = (\phi, p, e, D)$

It is clearly inefficient if the thread is created and destroyed repeatedly every period

- Some op. systems (funkOS) and programming languages (Real-time Java & Ada) support *periodic threads*
  - the kernel (or VM) reinitializes such a thread and puts it to sleep when the thread completes
  - The kernel releases the thread at the beginning of the next period
  - This provides clean abstraction but needs support from OS
- Thread instantiated once, performs job, sleeps until next period, repeats
  - Lower overhead, but relies on programmer to handle timing
  - Hard to avoid timing drift due to sleep overruns
    (see the discussion of delays earlier in this lecture)
  - Most common approach

Sporadic and Aperiodic Tasks

Events trigger sporadic and aperiodic tasks

- Might be extenal (hardware) interrupts
- Might be signalled by another task

Usual implementation:

- OS executes periodic server thread

  (background server, deferrable server, etc.)
- OS maintains a "server queue" = a list of pointers which give starting addresses of functions to be executed by the server
- Upon the occurrence of an event that releases an aperiodic or sporadic job, the event handler (usually an interrupt routine) inserts a pointer to the corresponding function to the list

Real-Time Programming & RTOS

Real-Time Operating systems

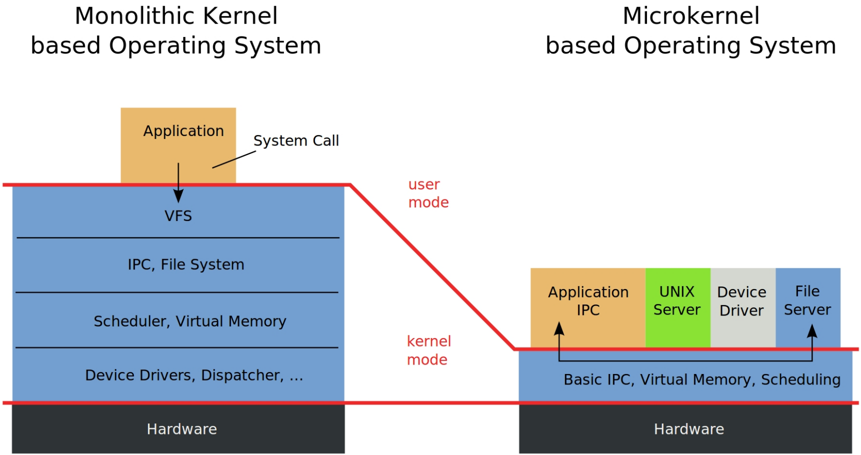
Operating Systems – What You Should Know ...

An operating system is a collection of software that manages computer hardware resources and provides common services for computer programs.

Basic components multi-purpose OS:

- Program execution & process management
  processes (threads), IPC, scheduling, ...
- Memory management
  segmentation, paging, protection ...
- Storage & other I/O management
  files systems, device drivers, ...
- Network management
  network drivers, protocols, ...
- Security
  user IDs, privileges, ...
- User interface
  shell, GUI, ...

Operating Systems – What You Should Know ...



Implementing Real-Time Systems

- Key fact from scheduler theory: *need predictable behavior*
  - Raw performance less critical than consistent and predictable performance; hence focus on scheduling algorithms, schedulability tests
  - Don't want to fairly share resources – be unfair to ensure deadlines met
- Need to run on a wide range of – often custom – hardware
  - Often resource constrained:
    limited memory, CPU, power consumption, size, weight, budget
  - Closed set of applications
    (Do we need a wristwatches to play DVDs?)
  - Strong reliability requirements – may be safety critical
  - How to upgrade software in a car engine? A DVD player?

Implications on Operating Systems

- General purpose operating systems not well suited for real-time
  - Assume plentiful resources, fairly shared amongst untrusted users
  - Serve multiple purposes
  - Exactly opposite of an RTOS!
- Instead want an operating system that is:
  - Small and light on resources
  - Predictable
  - Customisable, modular and extensible
  - Reliable

... and that can be *demonstrated* or *proven* to be so

Implications on Operating Systems

- Real-time operating systems typically either *cyclic executive* or *microkernel* designs, rather than a traditional monolithic kernel
  - Limited and well defined functionality
  - Easier to demonstrate correctness
  - Easier to customise
- Provide rich support for concurrency & real-time control
- Expose low-level system details to the applications

  control of scheduling, interaction with hardware devices, ...

Cyclic Executive without Interrupts

- The simplest real-time systems use a “nanokernel” design
  - Provides a minimal time service: scheduled clock pulse with a fixed period
  - No tasking, virtual memory/memory protection etc.
  - Allows implementation of a static cyclic schedule, provided:
    - Tasks can be scheduled in a frame-based manner
    - All interactions with hardware to be done on a polled basis
- Operating system becomes a single task cyclic executive

```
setup timer
c = 0;
while (1) {
        suspend until timer expires
        c++;
        do tasks due every cycle
        if (((c+0) % 2) == 0) do tasks due every 2nd cycle
        if (((c+1) % 3) == 0) {
                do tasks due every 3rd cycle, with phase 1
        }
        ...
}
```

Microkernel Architecture

- Cyclic executive widely used in low-end embedded devices
  - 8 bit processors with kilobytes of memory
  - Often programmed in (something like) C via cross-compiler, or assembler
  - Simple hardware interactions
  - Fixed, simple, and static task set to execute
  - Clock driven scheduler
- But many real-time embedded systems are more complex, need a sophisticated operating system with priority scheduling
- Common approach: a *microkernel* with priority scheduler

  Configurable and robust, since architected around interactions between cooperating system servers, rather than a monolithic kernel with ad-hoc interactions

Microkernel Architecture

- A microkernel RTOS typically provides:
  - Timing services, interrupt handling, support for hardware interaction
  - Task management, scheduling
  - Messaging, signals
  - Synchronization and locking
  - Memory management (and sometimes also protection)

Example RTOS: FreeRTOS

- RTOS for embedded devices (ported to many microcontrollers from more than 20 manufacturers)
- Distributed under GPL
- Written in C, kernel consists of 3+1 C source files (approx. 9000 lines of code including comments)
- Largely configurable

Example RTOS: FreeRTOS

- The OS is (more or less) a library of object modules;
  the application and OS modules are linked together in the resulting executable image
- Prioritized scheduling of tasks
  - tasks correspond to threads (share the same address space; have their own execution stacks)
  - highest priority executes; same priority ⇒ round robin
  - implicit *idle task* executing when no other task executes ⇒ may be assigned functionality of a background server
- Synchronization using semaphores
- Communication using message queues
- Memory management
  - no memory protection in basic version (can be extended)
  - various implementations of memory management
    memory can/cannot be freed after allocation, best fit vs combination of adjacent memory block into a single one

That's (almost) all ....

Example RTOS: FreeRTOS

Tiny memory requirements: e.g. IAR STR71x ARM7 port, full optimisation, minimum configuration, four priorities ⇒

- size of the scheduler = 236 bytes
- each queue adds 76 bytes + storage area
- each task 64 bytes + the stack size

Details of FreeRTOS Scheduling

- The scheduler must be explicitly invoked by calling `void vTaskStartScheduler(void)` from `main()`.

  The scheduler may also stop either due to error, or if one of the tasks calls `void vTaskEndScheduler(void)`.

- It is possible to create a new task by calling

```
portBASE_TYPE xTaskCreate(
    pdTASK_CODE pvTaskCode,
    const char * const pcName,
    unsigned short usStackDepth,
    void *pvParameters,
    unsigned portBASE_TYPE uxPriority,
    xTaskHandle *pvCreatedTask);
```

  `pvTaskCode` is a pointer to a function that will be executed as the task, `pcName` is a human-readable name of the task, `usStackDepth` indicates how many words must be reserved for the task stack, `pvParameters` is a pointer to parameters of the task (without interpretation by the OS), `uxPriority` is the assigned priority of the task (see resource control lecture 7), `pvCreatedTask` is the task handle used by OS routines.

Details of FreeRTOS Scheduling

- A task can be deleted by means of
  `void vTaskDelete(xTaskHandle pxTaskToDelete)`
  - Like most other (non-POSIX-compliant) small real-time systems, does not provide a task cancellation mechanism, i.e. tasks cannot decline, or postpone deletion – the deletion is immediate.
  - Memory is not freed immediately, only the idle task can do it that must be executed occasionally.
  - A shared resource owned by a deleted task remains locked.
- Priorities are handled by means of `uxTaskPriorityGet` and `uxTaskPrioritySet`. FreeRTOS implements priority inheritance protocol, the returned priorities are the current ones.
- Tasks can be

  suspended `vTaskSuspend` or `vTaskSuspendAll`

  (suspends of but the calling one),

  and resumed by `vTaskResume` or `vTaskResumedAll`.

  Suspend/resume all can be used to implement non-preemptable critical sections.

Clocks & Timers in FreeRTOS

- `portTickType xTaskGetTickCount(void)`

  Get current time, in ticks, since the scheduler was started.

  The frequency of ticks is determined by `configTICK_RATE_HZ` set w.r.t. the HW port.

- `void vTaskDelay(portTickType xTicksToDelay)`

  Blocks the calling task for the specified number of ticks.

- ```
  void vTaskDelayUntil(
      portTickType *pxPreviousWakeTime,
      portTickType xTimeIncrement
      );
  ```

  Blocks the calling process for `xTimeIncrement` ticks since the `pxPreviousWakeTime`.

  (At the wakeup, the `pxPreviousWakeTime` is incremented by `xTimeIncrement` so that it can be readily used to implement periodic tasks.)
  ```

Real-Time Programming & RTOS

Real-Time Programming Languages

Brief Overview

C and POSIX

IEEE 1003 POSIX

- "Portable Operating System Interface"
- Defines a subset of Unix functionality, various (optional) extensions added to support real-time scheduling, signals, message queues, etc.
- Widely implemented:
  - Unix variants and Linux
  - Dedicated real-time operating systems
  - Limited support in Windows

Several POSIX standards for real-time scheduling

- POSIX 1003.1b ("real-time extensions")
- POSIX 1003.1c ("pthreads")
- POSIX 1003.1d ("additional real-time extensions")
- Support a sub-set of scheduler features we have discussed

POSIX Scheduling API (Threads)

```
#include <unistd.h>
#include <pthread.h>

int pthread_attr_init(pthread_attr_t *attr);

int pthread_attr_getschedpolicy(pthread_attr_t *attr, int policy);
int pthread_attr_setschedpolicy(pthread_attr_t *attr, int policy);

int pthread_attr_getschedparam(pthread_attr_t *attr, struct sched_param *p);
int pthread_attr_setschedparam(pthread_attr_t *attr, struct sched_param *p);

int pthread_create(pthread_t      *thread,
                   pthread_attr_t *attr,
                   void *(*thread_func)(void*),
                   void   *thread_arg);
int pthread_exit(void *retval);
int pthread_join(pthread_t thread, void **retval);
```

`struct sched_param` typically contains only `sched_priority`.

`pthread_join` suspends execution of the thread until termination of the `thread`; `retval` of the terminating thread is available to any successfully joined thread.

Threads: Example I

```
#include <pthread.h>

pthread_t id;
void *fun(void *arg) {
  // Some code sequence
}

main() {
  pthread_create(&id, NULL, fun, NULL);
  // Some other code sequence
}
```

Threads: Example II

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS     5

void *PrintHello(void *threadid)
{
   printf("\n%d: Hello World!\n", threadid);
   pthread_exit(NULL);
}

int main (int argc, char *argv[])
{
   pthread_t threads[NUM_THREADS];
   int rc, t;
   for(t=0; t<NUM_THREADS; t++){
      printf("Creating thread %d\n", t);
      rc = pthread_create(&threads[t], NULL, PrintHello, (void *)t);
      if (rc){
         printf("ERROR; return code from pthread_create() is %d\n", rc);
         exit(-1);
      }
   }
   pthread_exit(NULL);
}
```

POSIX: Synchronization and Communication

- Synchronization:
  - mutexes
    (variables that can be locked/unlocked by threads),
  - (counting) semaphores,
  - condition variables,
    (Used to wait for some condition. The waiting thread is put into a queue until signaled on the condition variable by another thread.)
  - ...
- Communication:
  - signals (`kill(pid,sig)`),
  - message passing,
  - shared memory.

POSIX: Real-Time Support

Getting Time

- `time()` = seconds since Jan 1 1970
- `gettimeofday()` = seconds + nanoseconds since Jan 1 1970
- `tm` = structure for holding human readable time

```
struct tm {
  int    tm_sec;      // seconds (0 - 60)
  int    tm_min;      // minutes (0 - 59)
  int    tm_hour;     // hours (0 - 23)
  int    tm_mday;     // day of month (1 - 31)
  int    tm_mon;      // month of year (0 - 11)
  int    tm_year;     // year - 1900
  int    tm_wday;     // day of week (Sunday = 0)
  int    tm_yday;     // day of year (0 - 365)
  int    tm_isdst;    // is summer time in effect?
  char *tm_zone;      // timezone name
  long   tm_gmtoff;   // offset from UTC
};
struct tm localtime(time_t t);
time_t    mktime(struct tm *t);
```

- POSIX requires at least one clock of minimum resolution 50Hz (20ms)

POSIX: High Resolution Time & Timers

High resolution clock. Known clock resolution.

```
struct timespec {
    time_t tv_sec;
    long   tv_nsec;
}

int clock_gettime( clockid_t clock_id,
                   struct timespec * tp );
int clock_settime( clockid_t id,
                   const struct timespec * tp );
```

Simple waiting: `sleep`, or

```
int nanosleep(struct timespec *delay, struct timespec *remaining);
```

Sleep for the interval specified. May return earlier due to signal (in which case `remaining` gives the remaining delay).

Accuracy of the delay not known (and not necessarily correlated to `clock_getres()` value)

POSIX: Timers

- type `timer_t`; can be set:
  - relative/absolute time
  - single alarm time and an optional repetition period
- timer “rings” according to `sevp` (e.g. by sending a signal)

```
int timer_create(clockid_t clockid, struct sigevent *sevp,
                 timer_t *timerid);
```

```
int timer_settime(timer_t timerid, int flags,
                  const struct itimerspec *new_value,
                  struct itimerspec * old_value);
```

where

```
struct itimerspec {
             struct timespec it_interval;  /* Timer interval */
             struct timespec it_value;     /* Initial expiration */
         };
```

POSIX Scheduling API

- Four scheduling policies:
  - `SCHED_FIFO` = Fixed priority, pre-emptive, FIFO on the same priority level
  - `SCHED_RR` = Fixed priority, pre-emptive, round robin on the same priority level
  - `SCHED_SPORADIC` = Sporadic server
  - `SCHED_OTHER` = Unspecified (often the default time-sharing scheduler)
- A process can `sched_yield()` or otherwise block at any time
- POSIX 1003.1b provides (largely) fixed priority scheduling
  - Priority can be changed using `sched_set_param()`, but this is high overhead and is intended for reconfiguration rather than for dynamic scheduling
  - No direct support for dynamic priority algorithms (e.g. EDF)
- Limited set of priorities:
  - Use `sched_get_priority_min()`, `sched_get_priority_max()` to determine the range
  - Guarantees at least 32 priority levels

Using POSIX Scheduling: Rate Monotonic

Rate monotonic and deadline monotonic schedules can be naturally implemented using POSIX primitives

1. Assign priorities to tasks in the usual way for RM/DM
2. Query the range of allowed system priorities `sched_get_priority_min()` and `sched_get_priority_max()`
3. Map task set onto system priorities
   Care needs to be taken if there are large numbers of tasks, since some systems only support a few priority levels
4. Start tasks using assigned priorities and `SCHED_FIFO`

There is no explicit support for indicating deadlines, periods

EDF scheduling not supported by POSIX

Using POSIX Scheduling: Sporadic Server

POSIX 1003.1d defines a hybrid sporadic/background server

```
struct sched_param {
  int             sched_priority;
  int             sched_ss_low_priority;
  struct timespec sched_ss_repl_period;
  struct timespec sched_ss_init_budget;
};
```

When server has budget, runs at `sched_priority`, otherwise runs as a background server at `sched_ss_low_priority`

Set `sched_ss_low_priority` to be lower priority than real-time tasks, but possibly higher than other non-real-time tasks in the system

Also defines the replenishment period and the initial budget after replenishment

POSIX-compliant RTOS

Examples of POSIX-compliant implementations:

- commercial:
  - VxWorks
  - QNX
  - OSE
- Linux-related:
  - RTLINUX
  - RTAI

Latency

(Some) sources of hard to predict latency caused by the system:

- Interrupts
  see next slide
- System calls
  RTOS should characterise WCET; kernel should be preemptable
- Memory management: paging
  avoid, either use segmentation with a fixed memory management scheme, or memory locking
- Caches
  may introduce non-determinism; there are techniques for computing WCET with processor caches
- DMA
  competes with processor for the memory bus, hard to predict who wins

Interrupts

The amount of time required to handle interrupt varies

Thus in most OS, interrupt handling is divided into two steps

- Immediate interrupt service
  very short; invokes a scheduled interrupt handling routine
- Scheduled interrupt service
  preemptable, scheduled as an ordinary job at a suitable priority

Immediate Interrupt Service

Interrupt latency is the time between interrupt request and execution of the first instruction of the interrupt service routine

The total delay caused by interrupt is the sum of the following factors:

- the time the processor takes to complete the current instruction, do the necessary chores (flush pipeline and read the interrupt vector), and jump to the trap handler and interrupt dispatcher
- the time the kernel takes to disable interrupts
- the time required to complete the immediate interrupt service routines with higher-priority interrupts (if any) that occurred simultaneously with this one
- the time the kernel takes to save the context of the interrupted thread, identify the interrupting device, and get the starting address of the interrupt service routine
- the time the kernel takes to start the interrupt service routine

Event Latency