Real Time Kernels and Operating Systems

Introduction

Typical embedded system solves a complex problem
- By decomposing it into a number of smaller simpler pieces
  - That work together in an organized way
- Such pieces called *tasks*

With multiple tasks system called a *multitasking* system

Several important responsibilities of a multitasking design include
- *Exchanging / sharing* data between tasks
- *Synchronizing* tasks
- *Scheduling* task their execution
- *Sharing resources* amongst the tasks

Operating System
- Piece of software that provides the required coordination
- When the control must ensure that task execution
  - Satisfies a set of specified time constraints
  - Called a *real-time* operating system

- Primary software modules within an operating system
  - That implement such control
    - ✓ Scheduler
    - ✓ Dispatcher
    - ✓ Intertask communication

- *Scheduler*
  - Determines
    - Which task will run
    - When task will run
- *Dispatcher*
  - Performs necessary operations
    - To start task

- *Intertask Communication*
  - Mechanism for exchanging
    - Data and information between
      - Tasks or processes
        - Same machine
        - Different machines

Kernel
- Smallest portion of operating system
  - Provides above services

Full Featured Operating System

Provides additional libraries of functions

Device drivers

Rich communication packages

Human computer interface

Real Time Operating System - RTOS

Real time operating system is a special purpose operating system

Implies rigid time requirements must be met

If requirements not met results system functionality

Inaccurate

Compromised

Such systems usually interacting with physical environment

Sensors

Measurement devices

Usually in scientific experiments or control systems

Often people misuse term real time to mean system responds quickly

Come in two flavors

Hard Real Time

System delays are known or at least bounded

Said to be operating correctly if can return results

Within any time constraints

Soft Real Time

Critical tasks get priority over other tasks

Retain priority until complete

Real time task cannot be kept waiting indefinitely

Tasks with time constraints

Makes it amenable to mixing with other kinds of systems

Programs and Processes

With the quick introductory overview of OS features and responsibilities

Move inside

Examine programs and processes

What is a program…what is a process

Let's see

We have all worked with software programs

Program is not a process

Program is *passive* entity

Process is an *active* entity

A process is a program in execution
Execution proceeds in sequential manner
- Single instruction at a time

Process includes more than just program code
- Additionally includes
  - State or program counter
    - Which instruction is being executed
  - Contents of program's registers
    - Working variables
  - Process stack
    - Temporary data
      - Auto variables
      - Subroutine parameters
      - Return addresses
  - Data section
    - Reference to global variables
  - Code section
    - Reference to program instructions

- Actually most of these are soft copies
  - Of what may be held in pieces of hardware and used
    - While process executing

- Program may have several processes associated
  - Each is considered to be a separate execution sequence

An embedded program is similarly a static entity
- Made up of a collection of firmware modules
- Can do no useful work unless it is *running* or *executing*
  - Unless there are processes

When a firmware module is executing
- Again called a *process* or *task*

When a process is created
- It is allocated a number of resources by the system
  - Can include
    - ✓ Process stack
    - ✓ Memory address space
    - ✓ Registers (through the CPU)
    - ✓ Program counter
    - ✓ I/O ports
    - ✓ Network connections
    - ✓ File descriptors, etc

Resources generally not shared with other processes

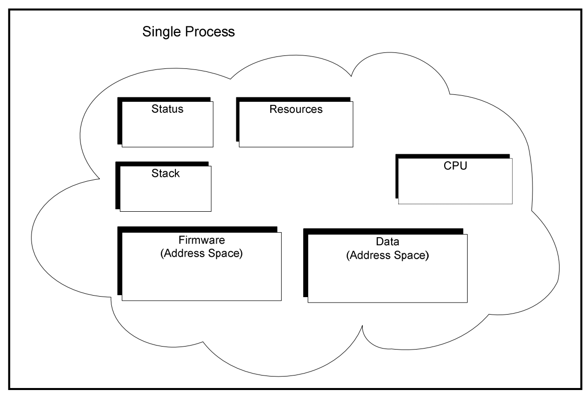
During execution
Contents of the program counter are continually changing
As the process moves from instruction to instruction
Working with *data*
Currently executing instruction and present values of associated
Collectively known as the *process state*
Process state may contain
Values of large number of other pieces of information
As noted already

Resources and the CPU as a Resource

Traditional view of computing focuses on the *program* not the *processes*
One says that the *program*, running on the computer
More specifically a task within program
Set of processes comprising program

With embedded application
Change the point of view from firmware to that of the microprocessor

Viewed with respect to the microprocessor
More specifically the CPU
CPU is simply another resource
Available for use by the task
To do its job



When a task enters the system
Takes up space – memory
Uses other system resources

Time that it takes to complete
Called its *execution time*
Its *persistence* is duration
From the time when it enters the system
Until it *terminates*

Single Task

If there only single process or task in system
No contention for resources
No restrictions on how long it can run
How much memory it uses

Second Task

If a second process or task is added to the system

Potential resource contention problems arise
Generally only one CPU and the remaining resources limited

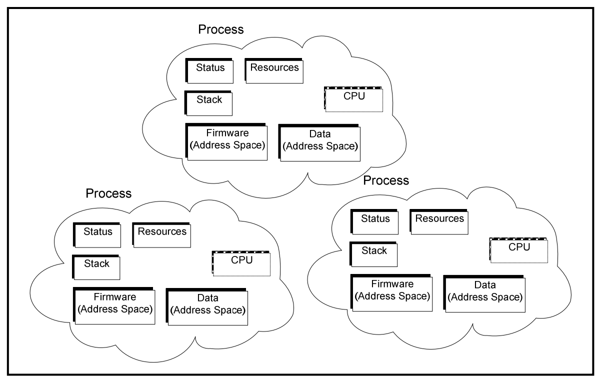
Problem resolved by
Carefully managing how the resources are allocated to each task
Controlling how long each can retain the resources
If each task shares the system's resources
Each can get its job finished

If the CPU is passed between the tasks quickly enough
Will appear as if both tasks using it at same time

Will have system that models parallel operations
By time sharing a single processor

Certainly, the execution time for the program will be extended
However operation will give *appearance* of simultaneous execution

Such a scheme is called *multitasking*
Tasks said to be running *concurrently*.



Multiple Tasks

Concept can easily be extended to more than two processes or tasks

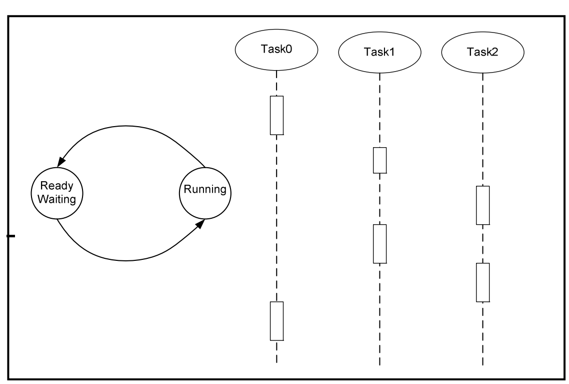
Implementing Control – A First Look

Under such a scheme
CPU is most important resource

In addition to the CPU however
Processes or tasks are sharing other system resources as well
Timers
I/O facilities
Busses

Despite the illusion that all of the tasks are running simultaneously
In reality at any instant in time
Only one process is actively executing
That process said to be in *run* state
Other process(es) in the *ready waiting* state

Such behavior is illustrated in the state and sequence diagrams
For system with three tasks
One task will be running



Others are waiting to be given the CPU

With ability to share CPU among several tasks
Problem
Deciding which task will be given the CPU
When task will be given the CPU

Solution
Schedule is set up to specify
- ✓ When
- ✓ Under what conditions
- ✓ For how long each task will be given use of CPU
  Other resources

Criteria for deciding / controlling which task is to run next
Collectively called a *scheduling strategy*

For embedded system such strategies generally fall into three categories
Multiprogramming
*R*unning task continues
Until it performs an operation that requires waiting for an external event
e.g. waiting for an I/O event or timer to expire

Real-Time
Tasks with specified temporal deadlines
Guaranteed to complete before those deadlines expire
Systems using such a scheme
Require a response to certain events
Within a well defined and constrained time

Time-sharing
Running task is required to give up the CPU
So that another task may get a turn
Under a time-shared strategy
Hardware timer used to *preempt* the currently executing task
Return control to the operating system

Such a scheme permits one to reliably ensure
Each process is given slice of time to use operating system

Process State – Changing Context

Observed earlier: process is a program in execution
Program in execution
Comprises active processes
As process executes it's often changing state

Specifically at any time may be in any one of following states

- New
    - Just being created
    - Running
- Instructions being executed
- Waiting
    - Waiting for some event to occur
        - I/O fetch for example
- Ready
    - Waiting to be assigned to processor
- Terminated
    - Finished execution

Task's *context* comprises
- Important information about the state of the task
    - Values of any variables
        - Held in the CPU's registers
    - Value of the program counter
    - State of the stack
    - Etc.

Each time
- Running task is stopped – *preempted* or *blocked*
    - CPU is given to another task
        - That is *ready*
    - *Switch* to a new *context* is executed

Context switch first requires
- State of the currently active task be saved

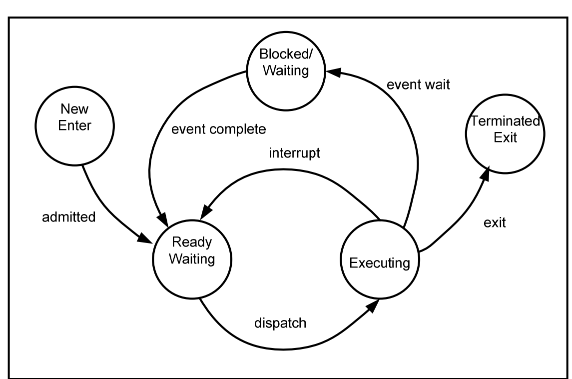
If task scheduled to get CPU had been running previously
- Its state is *restored*
- Continues where it had left off

Otherwise the new task starts from its initial state

As is evident context change
- Entails a lot of work
- Can take a significant amount of time

Earlier state diagram is now extended to reflect
- ✓ Task entering the system
- ✓ Being preempted
- ✓ Terminating

In multiprogrammed system
- Objective to have some processes running at all times
- Such scheme



        - Maximizes CPU usage

- As process *Enters* system
    - Put into job queue
- All jobs in system
    - Contained in *job queue*
        - User
        - System
    - *Ready and Waiting* processes in main memory
        - Placed in *ready queue*
        - Generally implemented as linked list
            - Task or Process Control Blocks
            - Each TCB (PCB) pointer field points to next job in queue

    - Other queues may exist in system as well
        - Processes waiting for particular resource
            - Placed in queue for that resource
        - Often called *device queue*

    - New process initially put into ready queue
        - Until selected for execution
        - At such time
            - *Dispatched* - given the CPU to execute

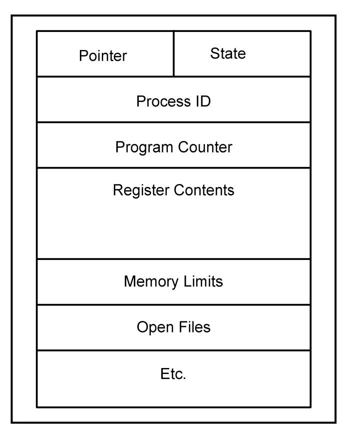
    - Dispatched process may have several events occur
        - Issue I/O request and be placed in I/O queue
        - Create new Child subprocess(es)
            - Wait for their termination
        - Could be returned to ready queue by CPU

        - In first two cases process enter *Waiting* state
            - Eventually switch from *Waiting* to *Ready* state
                - Returned to *ready queue*

    - Termination
        - When process (is) *Terminated*
            - Removed from all queues
            - TCB and resources
                - Deallocated

Task – Process Control Block

- In tasked based approach
    - Each process represented in the operating system
        - By a data structure called *Task Control Block – TCB*
            - also known as a *process control block*



TCB contains all of the important information about the task

- ✓ A typical TCB contains following information
- ✓ Pointer (for linking the TCB to various queues)
- ✓ Process ID and state
- ✓ Program counter
- ✓ CPU registers
- ✓ Scheduling information (priorities and pointers to scheduling queues)
- ✓ Memory management information (tag tables and cache information)
- ✓ Scheduling information (time limits or time and resources used)
- ✓ I/O status information (resources allocated or open files)

TCB allocation may be static or dynamic

- Static allocation

    Typically used in embedded systems with no memory management
    Are a fixed number of task control blocks
    Memory is allocated at system generation time
    Placed in dormant or unused state.

    When a task initiated
    TCB created
    Appropriate information entered

    TCB is then placed into *ready* state by scheduler

    From the ready state
    Will be moved to the *execute* state by dispatcher

    When a task terminates
    Associated TCB returned to *dormant* state

With fixed number of TCBs
No runtime memory management is necessary
One must be cautious not to exhaust supply of TCBs

- With dynamic allocation

    Variable number of task control blocks
    Allocated from the heap at runtime

    When a task initiated
    TCB created
    Appropriate information entered

    TCB is then placed into *ready* state by scheduler

- From the ready state
  - Will be moved to the *execute* state by dispatcher

- When a task terminates
  - Associated TCB memory is returned to heap storage
  - With a dynamic allocation
    - Heap management must be supported

- Dynamic allocation suggests an unlimited supply of TCBs
  - However the typical embedded application has limited memory
    - Allocating too many TCBs can exhaust the supply

- Dynamic memory allocation scheme
  - Generally too expensive for smaller embedded systems

Queues

- When a task enters the system
  - Typically be placed into a queue called the *Entry Queue* or *Job Queue*

- Easiest and most flexible way to implement such a queue
  - Utilize a linked list as the underlying data structure
  - Last entries in the TCB
    - Hold the pointers to the preceding and succeeding TCBs

- Whether queue, an array, or some other data type used to hold TCBs
  - Entries must all look alike
    - Such a requirement will impose some restrictions on implementation

- In C
  - TCB is implemented as a struct
    - Containing pointers to all relevant information
    - Because the data members of a struct must all be of the same type
      - Pointers are all void* pointers.
  - Skeletal structure for a typical TCB identifying essential elements
    - Task
    - Example set of task data
  - Given in the following C declarations

```
// The task control block
struct TCB
{
      void (*taskPtr)(void* taskDataPtr);
      void* taskDataPtr;
      void* stackPtr;
      unsigned short priority;
      struct TCB* nextPtr;
      struct TCB* prevPtr
};

// The data passed into the task
struct taskData
{
      int taskData0;
      int taskData1;
      char taskData2
};
// The task
void aTask(void* taskDataPtr)
{
      function body;
}
```

Threads – Lightweight and Heavyweight

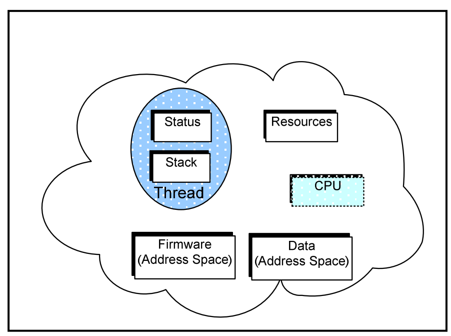
Task or process characterized by
- Collection of resources utilized to execute program

Thread
- Smallest subset of these resources necessary for the execution of the program
- Copy of the CPU registers
  - Including the program counter and a stack

Sometimes the subset of resources
- Called a *lightweight thread*

In contrast to the process itself
- Referred to as a *heavyweight thread*

Thread can be in only one process
Process without a thread can do nothing



Single Thread
- Sequential execution of a set of instructions
  - Through a task or process in an embedded application
    - Called a *thread of execution*, or *thread of control*

- *Thread*
  - Has a stack and status information relevant to its state and operation
  - *Copy* of the (contents of) the physical registers

  - During execution uses
    - Code (firmware)
    - Data

CPU (and associated *physical* registers)
Other resources allocated to the process

Diagram presents
Single task with one thread of execution

Model is referred to as a *single process – single thread design*.

When we state that process is *running, blocked, ready,* or *terminated*
Are actually describing different states of thread

If embedded design intended to perform a wide variety of operations
With minimal interaction
May be appropriate to allocate one process
To each major function to be performed

Such systems ideal for *multi process – single thread* implementation

Multiple Threads

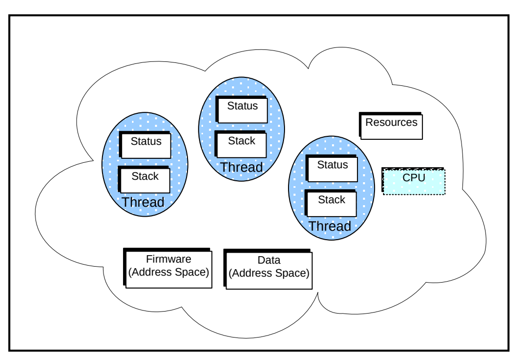
Many embedded systems intended to perform single primary function
Operations performed by function all interrelated

During partitioning and functional decomposition
Seek to identify which actions benefit from parallel execution
Might consider allocating subtask for each type of I/O

Nature of application executing as a single primary function
Suggests that associated process should be decomposed
Into a number of subtasks
Executing in parallel

At runtime process can pass the CPU around to each of subtasks
Thereby enabling each to do its job

Each of the smaller jobs has its own thread of execution
Such a system called a *single process – multithread design*



Unlike processes or tasks
Threads are not independent of each other
Can access any address within the process
Including other thread's stacks
Why is this important to note?

Context switch between threads
Can be substantially simpler and faster
Than between processes

When switching between threads

Much less information must be saved and restored

An operating system that supports tasks with multiple threads

Referred to as a *multithreaded operating system*

Can easily extend design to support multiple processes

Can further decompose each process into multiple subtasks

Such a system called *multiprocess – multithread design*

Sharing Resources

Based upon discussions

Can identify four categories of multitasking operating system

- ✓ *Single process–single thread*
  Has only one process
  In embedded application that process runs forever

- ✓ A *multi process–single thread*
  Supports multiple simultaneously executing processes
  Each process has only single thread of control

- ✓ A *single process–multiple threads*
  Supports only one process
  Within the process has multiple threads of control

- ✓ A *multi processes – multiple threads*
  Supports multiple processes
  Within each process is support for multiple threads of control

Major distinguishing feature

Which resources process and hence thread(s) is / are using

Where the resources come from

At a minimum process or task will need

- ✓ Code or firmware – the instructions.
  Are in memory and have addresses.
- ✓ Data that the code is manipulating
  Starts out in memory
  May be moved to registers
  Data has addresses
- ✓ CPU and associated physical registers
- ✓ Stack
- ✓ Status information

First three items

Shared among member threads
Last two are proprietary to each thread

Each thread has *copy* of the registers
Often other necessary resources
Timers
Measurement
Signal generation resources
I/O ports etc.

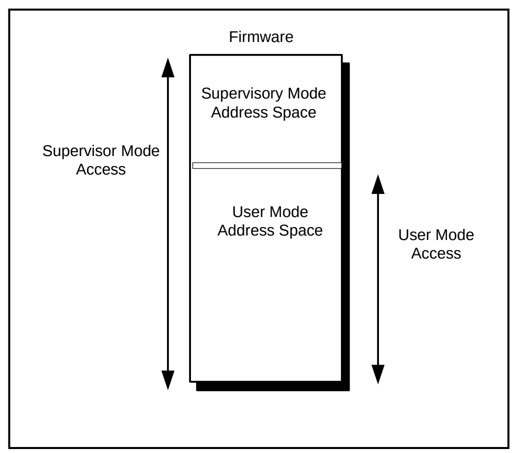
Memory Resource Management

System Level Management

After CPU
Memory probably most important resource available to a task
Spend some time to examine characteristics
Unique to embedded systems

Most microprocessor designs today still based upon von Neumann architecture
Program (instructions) stored memory
In same manner as any other piece of information (data)
With single physical memory
Instructions and data accesses
Use same physical bus
Limits execution speed

When process created by the operating system
Is given portion of physical memory in which to work
Set of addresses (a resource) delimiting that code and data memory
Proprietary to each process called its *address space*



Address space typically not shared
With any other peer processes

When multiple processes concurrently executing in memory
Errant pointer or stack error can easily lead to
Memory owned by other processes
Being inadvertently accessed
Overwritten
System software must restrict the range of addresses
Accessible to the executing process
Process (thread) trying to access memory
Outside its allowed range

Should be immediately stopped

Before it can inflict damage on memory belonging to other processes

One means by which such restrictions are enforced
Concept of *privilege level*

Processes are segregated into
User mode capability
User mode limits the subset of instructions process can use
Supervisor mode capability
Can access entire memory space

Processes with low (user mode) privilege level
Not allowed to perform certain kinds of memory accesses
Not allowed to execute certain instructions

When a process attempts to execute such restricted instructions
An interrupt is generated
Supervisory program with a higher privilege level
Decides how to respond

Supervisor mode privilege level
Generally reserved for supervisory or administration types of tasks
Delegated to the operating system
Processes with such privilege
Have access to any firmware
Can use any instructions within the microprocessor's instruction set

Process Level Management

Process may create or spawn *child processes*
Parent process may choose to give a subset of its resources
To each of the children
Children are separate processes
Each has its own
- ✓ Data address space
- ✓ Data
- ✓ Status
- ✓ Stack

Code portion of address space shared

Process may create *multiple threads*
Parent process shares most of its resources
With each of the threads
Are not separate processes but separate threads of execution
Within the same process
Each thread will have

Its own stack and status information

In contrast to lightweight threads
Processes or tasks exist in separate address spaces
One must use some form of messaging or shared variable
For inter-task exchange

Processes have stronger notion of encapsulation than threads
Each *thread*
Has own CPU state
Shares with peer threads
Code section
Data section
Task resources
Sharing gives threads weaker notion of encapsulation

Re-entrant Code

Child processes and their threads
Share same firmware memory area
As a result two different threads
Can be executing the same function at the same time

Functions using *only* local variables
Inherently *re-entrant*
They can be simultaneously
Called and executed in two or more contexts

Local variables
Copied to stack
Each invocation will get new copies

Functions that use
Global variables
Variables local to the process
Variables passed by reference
Shared resources
Not re-entrant

One must ensure all accesses to any common resources are coordinated

When designing the application…must make certain
One thread cannot corrupt the values of the variables in a second
Any shared functions must be designed to be re-entrant

Design said to be *thread safe*
If code functions correctly

During simultaneously execution
By multiple threads
In same address space

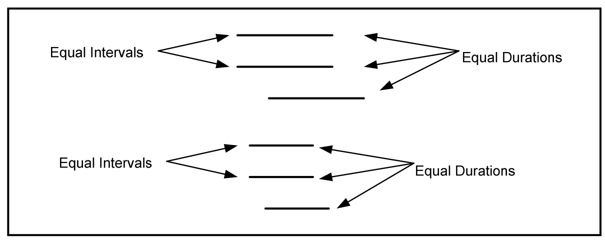
Controlling the System

In world of embedded systems
Can control operation of systems in number of different ways
Can loosely classify such systems into two broad categories
Time based
Reactive

Let's look at each

Time Based Systems

Systems whose behaviour controlled by time
Can be
Absolute
Relative
Following an interval



✓ Absolute time
Real world time

✓ Duration
Relative time measure
Non-equal intervals

✓ Interval
Distinct from duration
Interval marked by
Specific start and end times
Equal intervals have same start and stop
Can have same duration

Operating Systems

Operating system
Special and powerful subclass of time based systems
Types commonly found in embedded applications
Full operating system
Subset of full system
RTOS - Real time operating system
Special class of OS
With constraints on system level timing
Embedded *operating system* provides an environment
Within which firmware pieces – tasks are executed

Easiest way to first view an operating system
From the perspective of the services it can provide

Internally operating systems vary greatly
In both design and the strategy for delivering such services

Operating system must provide or support four specific functions.

- Schedule task execution
- Dispatch a task to run
- Ensure communication and synchronization amongst tasks
- Manage resources

Scheduler
Determines
Which task will run
When it will do so
Dispatcher
Performs the necessary operations to start task
Intertask or interprocess communication
Mechanism for exchanging data and information
Between tasks or processes
On the same machine
On different one

Kernel is the smallest portion of operating system
That provides these functions

Easiest way to view is from perspective of services provided
Include
<u>Process Management</u>
Creation and deletion of user and system processes
Suspension and resumption of processes
Manage interprocess communication
Handle and resolve deadlocks

<u>Main Memory Management</u>
Track which parts of memory are being used
Track which processes are loaded into memory
Allocate and deallocate memory space as needed

<u>Secondary Memory Management</u>
Manage free disk space
Storage allocation
Disk scheduling

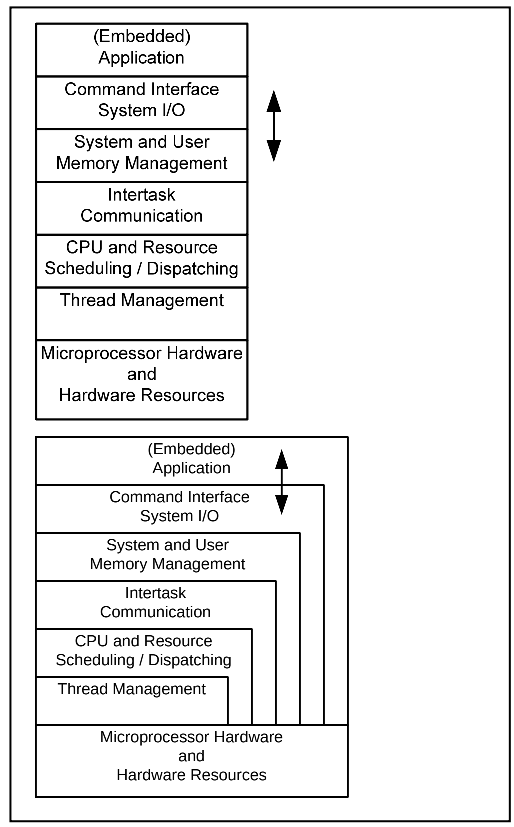
I/O System Management
- General device driver interface
- Caching and buffering of I/O
- Device drivers for specific devices

File System Management
- Creation and deletion of files
- Directory creation, deletion, and management
- Mapping onto secondary storage
- Backup onto nv storage

System Protection
- Managing concurrent users and processes
- Ensuring protection of data and resources

Networking
- Manages intrasystem communication and scheduling of tasks

Command Interpretation
- Provides the interface between the user and the operating system



Layering and Virtual Machines

- Most contemporary operating systems
  - Implemented using a layered approach
- Main advantage is increased modularity
- Layers are designed such that each layer
  - Uses functions / operations and services of lower layers
- Typical architecture appears as
  - Shown on left
- In some layered implementations
  - Such as that on right
  - Higher level layers have access to lower level
    - System calls
    - Hardware instructions
  - With such capability
    - Can make application programmers interface
      - Appear to be machine itself
  - Can logically extend concept
    - Using scheduling and virtual memory concepts
    - Can create illusion
      - Each program running on its own machine
      - Called *virtual machine* concept

With such a machine
No reason why could not run entirely different
Operating system
DOS on UNIX
Associated software packages

Virtual machine can be difficult to implement in general
Not always a good match between
Hardware
3 disk drives for example
Virtual machines
More than 3
Each can't have it's own drive
Must create virtual disks
Other more complex system level issues

Reactive or Foreground – Background Systems

Reactive systems
Comprise tasks
Initiated by some event
Internal or external to system

Internal event
Internal timer interrupt
May be elapsed time
Bound on data exceeded

External event
External world interrupt
Recognition of keystroke or switch activated
External response to internally generated command

Such systems do nothing until event occurs
Called *event driven* systems
The *foreground / background model* for managing task execution
Decomposes set of tasks into two subsets
Called *background tasks* and *foreground tasks*

Traditional decomposition
Foreground set
Tasks that interact with the user or other I/O devices

Background set
Remainder

Interpretation is slightly modified in the embedded world

- Foreground tasks
  Those initiated by interrupt or by a real-time constraint that must be met
  They will be assigned the higher priority levels in the system

- Background tasks
  Non-interrupt driven and are assigned the lower priorities
  Once started will typically run to completion
  Can be interrupted or preempted by any foreground task at any time

  Should include those that do not have tight time constraints
  Good candidates include tasks designed to
  Continuously monitor system integrity
  That involve heavy processing are

Often separate ready queues will be maintained for the two types of tasks

Representing Time

When considering either time-based or reactive systems
Time is important element

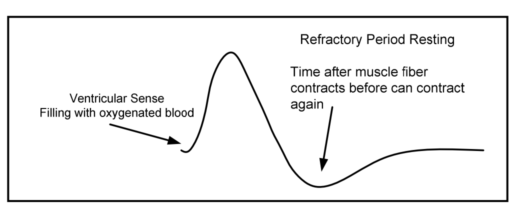
✓ Time based
When does something occur
How tightly can time intervals be held or met

✓ Reactive
How quickly can event be recognized
How quickly and repeatedly can event be responded to

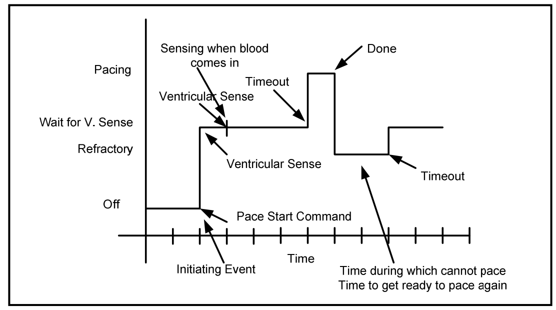
Issues of time important
When trying to schedule tasks and threads
Tasks or threads that are initiated
With repeating duration between invocations
Called *periodic*
Such duration called *period*
Time to complete called execution time
Variation in evoking event called *jitter*
Must examine each context to determine
Significance of jitter with respect to time constraints

Let's see how we can express this
Consider basic heart pace maker

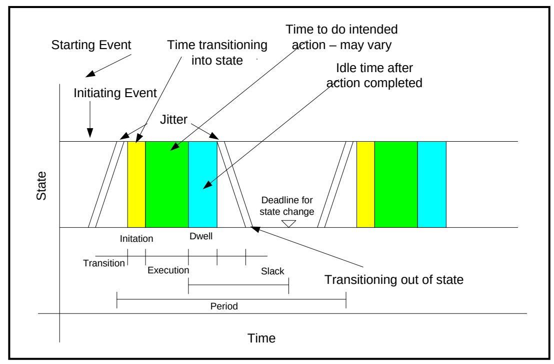
Figure illustrates Edmark wave of heartbeat



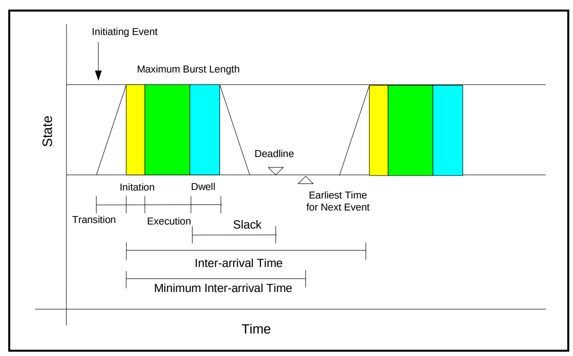
Normal operation
  Ventricular sense
    Hearting filling with oxygenated blood
  Pump
    Heart muscle contracts to pump blood
  Refractory period
    Muscle fiber relaxes
      Until can fill and contract



We can express changes in state in our systems
  In variety of different ways
    Timing diagram
    State chart
    Activity diagram



Simplest method probably a timing diagram
  Timing diagram in this context
    Different from what may have encountered
  Here we express behaviour of system
    Moving between states
  In basic diagram we express
    States along vertical axis
    Time along horizontal axis



We elaborate by annotating
  Durations
  Events
  Jitter
  State transitions
  Here we illustrate a periodic system

The sloped lines indicate transition between states
  Such transition potentially may be significant
    Most of time small compared to other times
  Observe how leading and trailing jitter represented

  Can show same thing for aperiodic sequence

    Note we specify min and max times

    Invocation of aperiodic tasks varies
      Duration between such tasks called *inter-arrival time*
    Such time is critical when determining how to schedule
      Real time tasks

    Under such circumstances

Must identify lower bound on inter-arrival time
May also need to consider such things as
Maximum number of events within given time interval

Thinking Schedule – A First Look

When working with scheduling system
Must address *priority* of task
Priority based upon different criteria
Will examine these shortly

Used to resolve which task to execute
When more than one task
Waiting and ready to execute

Tasks with higher priority
Execute preferentially over those with lower priority

Real time system one in which correctness implies timeliness
Most such systems carefully manage resources
To ensure maintaining *predictability*
Of the timeliness constraints
Predictability gives measure of accuracy
With which one can state in advance
When and how an action will occur
Thus schedule a real-time system

Task which must start or finish by specified time
Defined as *hard* or said to have a *hard deadline*
Missed deadline considered to be
Partial or total failure

✓ System is defined as *hard real-time*
If contains one or more such tasks
Such system may have other not or non hard real-time tasks
Major focus however on hard deadlines

✓ System with relaxed constraints defined as *soft real-time*
Such systems may meet deadline on average
Soft real-time systems may be soft in several ways

- Relaxation of constraint that missing deadline
  Constitutes system failure
  Such system may tolerate missing specific deadline
  Provided some other deadline or timeliness constraint met
  Average throughput for example
- May evaluate correctness of timeliness as
  Gradation of values rather that pass or fail

How bad did we miss deadline

✓ System with tasks having some constraints (but relaxed) as well as hard deadline
Defined as *firm real-time*

Task that can be determined to always meet timeliness constraint
Said to be *schedulable*
Task that can be guaranteed to always meet all deadlines
Said to be *deterministically schedulable*
Occurs when event's worst case response time
Less than or equal to task's deadline

When all tasks can be scheduled
Overall system can be scheduled
Does it matter
Following table captures timeliness constraints
With respect to whether task is soft or hard real-time

Property	*Non Real-time*	*Soft Real-time*	*Hard Real-time*
Deterministic	No	Possibly	Yes
Predictable	No	Possibly	Yes
Consequences of late computation	No effect	Degraded Performance	Failure
Critical reliability	No	Yes	Yes
Response dictated by external Events	No	Yes	Yes
Timing analysis possible	No	Analytic (sometimes), stochastic simulation	Analytic, stochastic simulation

Scheduling Tasks

With all this information in hand
Let's get to work and examine process of scheduling tasks

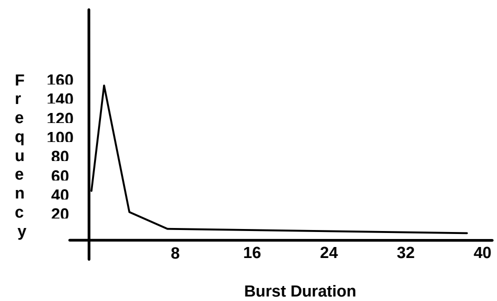
Scheduling comes in during design phase of our development
We decide the schedule
Involves decisions that affect and optimize
Overall performance of our system
According to some criteria
Given in the specification

When dealing with hard deadlines
Must ensure that such tasks and associated actions
Can meet every deadline

Soft deadlines
Give us more flexibility
Now focus is on trying to minimize items such as
Missed deadlines
Delay in initiating task

Success of CPU scheduling depends upon following
Observed property of processes
Process execution consists of cycle of
CPU execution
I/O wait
CPU and I/O bursts alternate until process completes

Frequency of bursts tends to be fairly predictable independent of
Machine or process
Generally characterized as exponential
Given in figure
Whenever CPU becomes idle
Which it may do during I/O times
Operating system must select process
From ready queue
To be executed
Process carried out by scheduler
According to predefined algorithm



CPU scheduling is basis of multi-programmed operating
By switching CPU among processes
Operating system makes computer more productive
Recall we refer to this as context switch
For real time systems
Time required for context switch critical

As noted our goal is to have some process running at all times
Whenever CPU becomes idle
Operating systems selects process in ready queue to execute
Note ready queue not necessarily a FIFO
Next (ready) job selected may be based upon other criteria
Priority
Basic queue with priority associated with each entry
Get from the head
Search the queue to find job that meets priority criteria
Return it

Scheduling Decisions

Two key elements of real-time design
Repeatability

Predictability
These are absolutely essential in context of hard deadlines

To ensure predictability
We must
Completely define the timing characteristics of tasks
Properly schedule using predictable scheduling algorithm
Not always easy as we'll see shortly

When do we select a new task to run

Preemptive vs Non-Preemptive Scheduling
Decisions made under following four conditions
1. Process switches from running to waiting states
   I/O request
2. Process switches from running to ready state
   When interrupt occurs
3. Process switches from waiting to ready
   Completion of I/O
4. Process terminates

If only using conditions 1 and 4
New process must be scheduled
Such scheduling called *non-preemptive*
Under such scheduling
Process keeps CPU until it releases
Terminating
Switching to waiting state
Otherwise scheduling called *preemptive*

Schedulers in real-time systems
Assign priority to each task
As noted earlier establishes precedence of task
When multiple tasks ready to run
Most common scheduling policy in such systems
Use preemptive scheduling
If lower priority task executing
Arriving higher priority task preempts
Lower priority task suspended
Resumes when higher priority task completes
Otherwise
Runs to completion

Although priority scheme seems to ensure
Higher priority tasks will always complete
Not always the case

With preemption problem of *blocking* arises
Blocking occurs when task needs resource
Owned by another task

Consider several examples
Case 1:
Task A has higher priority than task B
Task B starts and reserves resource R1
Task A preempts Task B
Task A begins execution and becomes blocked at point
Resource R1 needed
Task A must suspend and allow B to complete
Thereby releasing R1

Second case introduces problem called priority inversion
Problem of this nature occurred on one of Mars missions
Case 2:
We have 3 tasks
Task A, Task B, and Task C
Task A has highest priority and Task C the lowest
Task C starts and reserves resource R1
Task A preempts Task C
Task A begins execution and becomes blocked at point
Resource R1 needed
Task A must suspend and allow C to continue
Hopefully releasing R1
Task B preempts Task C and does not need R1
Task B completes
Allows Task C to resume
Easy to create situation in which highest priority task
Blocked forever
See that high priority task
That can be scheduled in isolation
May fail in multitasking context
In hard real-time context
Must ensure bound on priority inversion

Additional Scheduling Criteria

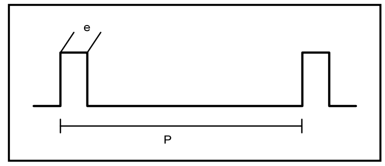
Must ask what is important
Number of different scheduling algorithms

In making choice must consider properties of various algorithms

Other properties include

- CPU utilization
  Want to keep as busy as possible

Ideally 100 per cent
In real system should range between
40% for lightly loaded system
90% for heavily loaded system
Also speak of utilization with respect to single task
For such a periodic task, Ti, utilization given as



$u_i = e_i / p_i$
u_I fraction of time task keeps CPU busy
e_i execution time
p_i for periodic task is the period
Can express similar relationship for aperiodic tasks

- Throughput
  Number of processes that are completed per unit of time
  Depends of course on complexity of process / task

- Turnaround Time
  Interval from time of submission of task until its completion
  Includes time
  Waiting to get into memory
  Waiting in ready queue
  Executing on CPU
  Doing I/O

- Waiting Time
  Scheduling algorithm execution and I/O time
  Affects only time spent in waiting queue
  Includes all time in waiting queue

- Response Time
  For interactive system
  Turnaround time may not be best measure
  Consider time from submission to first response
  Time take to first response not time to first output

Scheduling Algorithms

Beyond scope to go into details of all scheduling algorithms
Let's look at several however
We'll begin with very simplest

Polled and Polled with Timing Event

Simple kernel designed for use with single task
Although simple
Algorithm sometimes essential in cases
With hard deadline

Important to recognize the significance of time

Polled

- Among simplest and fastest
- System continually loops
    - Looking for event to occur
- Works well for single task
    - Deterministic
    - Time to respond to event
        - Computable
        - Bounded
            - Worst case
                - Assume event occurs immediately after test instruction
                - Response time is length of loop

Polled with Timing Event

- Simple extension
- Uses timing element
    - Delay action after polled event true
- Can be used to deskew signals

Timing Interrupt / Event Interrupt Driven

- System continually loops
    - Until interrupted by
        - Timing event
            - Typically internal signal
        - Interrupting event
            - Typically external signal
- Uses timing/interrupt event to trigger context switch
    - Hardware
    - Software
    - Timing
        - Periodic
            - Fixed rate scheduling
        - Aperiodic
            - Sporadic scheduling

- Can work with multiple tasks
    - Basis for time-sharing systems

- Tasks may or may not be equal
    - Periodic
        - All given same amount of time
    - Aperiodic
        - Time allocation based upon priority

First-Come-First-Served

Simple algorithm is first-come first-served
Easily managed with FIFO queue
When process enters ready queue
TCB linked to tail of queue
When CPU free
Allocated to process at head of the queue
Running process removed from queue
Is non-preemptive algorithm
Can be troublesome in real-time system

Shortest Job First

Assumes CPU used in bursts of activity
Each task has associated estimate of
How much time job will need when next given CPU
Estimate is based upon measured lengths of previous CPU usage
Can be either preemptive or non-preemptive
With preemptive schedule
Currently running process can be interrupted by one with
Shorter remaining completion time

Priority Schedule

Shortest job first
Special case of more general priority scheduling
Priority associated with each process
CPU allocated to process with highest priority
Equal priority jobs scheduled first-come first-serve
Major problem
As we've discussed have potential for
Indefinite blocking or starving
Priority inversion
Can be either preemptive or non-preemptive
Can make priority decisions
During design
Static schedule
During runtime
Dynamic schedule

- *Rate Monotonic*

With preemptive schedule
Currently running process is interrupted by one with
Higher priority
Special class called *rate-monotonic*
Initially developed in 1973
Updated over the years

In basic algorithm priority assigned based upon
Execution period
Shorter period – higher priority
Priorities determined and assigned at design time
Remain fixed during execution
Said to use *static* or *fixed* scheduling policy

We compute schedulability as bound on utilization of CPU
Sum on left hand side
Individual task utilizations
For n == 1
Have 100% utilization
As n $\rightarrow\infty$
Utilization $\rightarrow$ 69%

e and p
Execution time and period of task respectively

$$\boxed{\sum_{i=0}^{n-1} \frac{e_i}{p_i} \leq n\left(2^{\frac{1}{n}} - 1\right)}$$

Approach makes following assumptions
Deadline for each task
Equal to its period
All tasks preemptible at any time
The expression on right hand side
Gives bound on utilization
Establishes extreme bound
If cannot be met
Must execute more detailed analysis
To prove schedulability
Sets bound at 69% utilization
Practically could be relaxed to 88%
Still be scheduled

Basic algorithm given above
Simplifies system analysis
Scheduling is static
Worst case occurs when all jobs started simultaneously

Rate monotonic schedule – *critical zone theorem*

> If the computed utilization is less than the utilization bound, then the system is guaranteed to meet all task deadlines in all task phasings.

Can be shown rate-monotonic systems are
- Optimal fixed rate scheduling method
- If rate-monotonic schedule cannot be found
- No other fixed rate scheme will work

Stable
- Note: priority is based upon execution period

- As additional lower priority tasks added
  - Higher priority tasks can still meet deadline
    - Even if lower priority tasks fail to do so
  - Assumes no blocking

- Basic algorithm can be modified to include blocking

$$\boxed{\sum_{i=0}^{n-1} \frac{e_i}{p_i} + \max\left(\frac{b_0}{p_0},....,\frac{b_{n-1}}{p_{n-1}}\right) \le n\left(2^{\frac{1}{n}} - 1\right)}$$

Terms b_i give maximum time task i can be blocked
- By lower priority task

With non-preemptive schedule
- Currently arriving higher priority process
  - Placed at head of ready queue

- *Earliest Deadline*

  Earliest deadline uses a dynamic algorithm
  - Priority assigned based upon task with closest deadline

  Must be done during runtime
  - Only then can deadline(s) be assessed

  Set of tasks considered schedulable
  - Sum of task loading less than 100%

  Considered optimal
  - Sense if can be scheduled by other algorithms
    - Can be scheduled by Earliest Deadline

  Algorithm not considered stable
  - If runtime task load rises above 100%

Some task misses deadline
Generally not possible to predict which task will fail

Further adds runtime complexity
Scheduler must continually determine
Which task to execute next
Whenever such decisions must be made
Analytical methods more complex than fixed priority cases

- *Least Laxity*

This algorithm similar to earliest deadline
Constraint a little tighter
In addition to deadline
Considers time to execute task
Which task has least room to move

Thus
Priority based upon
laxity = deadline – execution time
Task with negative laxity
Cannot meet deadline

Schedule based upon ascending laxity
On paper rather straight forward concept
However means
Must know
Exact value or upper bound on execution time
Must update values
With each system change

Can utilize in system with hard and soft deadlines
Hard time tasks can be given priority
Over those with less rigid constraints

Has weaknesses similar to Earliest Deadline
Not stable
Greater run time burden than fixed schemes
Tends to devote CPU cycles to tasks
That are clearly going to be late
Causes more tasks to miss deadlines

- *Maximum-Urgency-First*

Algorithm includes features of
Rate Monotonic
Least Laxity

- First cut
  - Assign priority according to period
    - Same as Rate Monotonic

- Add binary *criticality* task parameter
  - Parameter does decomposition into two sets
    - Critical and non-critical
  - Least Laxity algorithm
    - Applied to those in critical set
      - Observe this is done at runtime

- If no critical tasks waiting
  - Tasks from non-critical set scheduled
- Because critical set based upon Rate Monotonic algorithm
  - Can structure so that no critical task
    - Fails to meet deadline

- Major advantage of algorithm
  - Simplicity of static priority
  - Reduced runtime burden compared with full Least Laxity

- Lacks some flexibility
  - Rate monotonic assumes unconstrained preemption
    - Short deviations typically tolerated well
    - Longer deviations
      - Can lead to missed deadlines
  - Best applied
    - Tasks well understood
    - Blocking constraints easy to determine
    - Dynamic scheduling contribution from Least Laxity
      - Potentially can compensate by elevating task's priority
- Has some of runtime complexity of pure Least Laxity

Round Robin

- Designed especially for timeshared systems
- Similar to first-come first-served
- Preemption added to switch between processes
- Small unit of time called *time quantum* or *slice* defined
- Ready queue treated as circular queue
  - Scheduler walks queue
    - Allocating CPU to process for 1 time slice
      - If process completes in less than allocated time
        - It releases CPU
      - Else the process is interrupted when time expires
        - Put at end of queue

New processes are added to tail of queue

Observe

If time slice increased to infinity

Becomes first-come first-served scheduler

Real Time Scheduling Considerations

Have noted real time system may be

Hard real time

Soft real time

Scheduling may be

Static

Dynamic

Hard Real Time

If dynamic

General process submitted along with statement

Time required to compute and do I/O

Scheduler

Accepts process

Guarantees can complete on time

Rejects as impossible

Called *resource reservation*

Requires scheduler to know exactly how long

Each operating system function takes

Requires completion time guarantee

Impossible for systems with

Secondary storage

Virtual memory

Soft Real Time

Less restrictive

Require critical processes to have priority

Over less critical

Implementing soft real-time system

Requires careful design of

Scheduler

Related aspects of operating system

Requires

Priority scheduling

Real time processes must have highest priority

Must not degrade over time

Relatively easy to ensure

Dispatch latency must be small

Requires system calls to be preemptible

Achieved several ways

Insert preemption points
Check if high priority process needs to be run
Make entire kernel preemptible
All kernel data structures must be protected
Synchronization methods
Comprised of two components
Conflict phase
Preemption of any process running in kernel
Low priority process releasing needed resources
Context switch to high priority process
Dispatch phase
Moving from ready state to run state

Algorithm Evaluation

As we've seen
There are many algorithms each with own parameters
Selecting difficult
Must first establish criteria
CPU utilization
Response time
Throughput
Next must evaluate algorithms against criteria
Variety of methods - let's examine several

Analytic Evaluation

Major class of methods called *analytic evaluation*
Uses algorithm and system workload
Produce formula or number to evaluate algorithm
For workload
One such method called *deterministic modeling*
Takes predetermined workload
Defines performance of each algorithm for workload
Consider following processes and workloads

Process	**Burst Time**
P1	10
P2	29
P3	3
P4	7
P5	12

Let's look at the following scheduling algorithms
First Come First Served
Shortest Job First
Round Robin

FCFS

P1 10	P2 29

P3 3	P4 7	P5 12

Waiting Times

Average = 28 units

Process	**Waiting Times**
P1	0
P2	10
P3	39
P4	42
P5	49

SJF

P3 3	P4 7	P1 10	P5 12

P 2 29

Waiting Times

Average = 13 units

Process	**Waiting Times**
P3	0
P4	3
P1	10
P5	20
P2	32

RR

Preempt every 10 time units

P1 10	P2 10	P3 3	P4 7	P5 10

P2 10	P5 2	P2 9

W
aiting Times

Average = 23 units

Process	**Waiting Times**
P1	0
P2	32
P3	20
P4	23
P5	40

Deterministic modeling
- Simple and fast
- Requires exact knowledge of process times
  - Often difficult to establish
  - One solution is to measure over repeated executions

Queuing Models

Processes run on many systems vary from day to day

No static set of processes and times
- For use in deterministic modeling

Can measure or compute distribution of CPU and I/O bursts

Have seen this is typically exponential
Can be described by a mean value
Can determine similar distribution for process arrival times
Based upon two distributions
For most algorithms possible to compute average
Throughput
Utilization
Waiting times
etc.
Can model computer as collection or network of servers
Each server has queue associated
Knowing arrival and service rate
Can compute
Utilization
Average queue length - n
Average wait time - w
Let average arrival time be λ
Thus
If system in steady state
Number of processes leaving = number of process arriving

$n = \lambda \times W$
Known as *Little's formula*
Useful because valid for any scheduling algorithm
Knowing any two variables
Can compute third

Useful for comparing algorithms
Has limitations
Mathematics of complex algorithms and distributions
Difficult to work with
Arrival and service distributions complex
Queuing models
Only approximation of real system

Simulation

To get more accurate evaluation of scheduling algorithm
Can use simulations
Requires
Models of computer system and processes
Data to drive simulation
Often collected from trace of actual processes
Recording of actual events
On real system
Can be expensive

Becoming increasingly powerful tool

Implementation

- Build and test
- Most accurate method
- Difficulty is cost
  - Development
  - System to support