CS 5372
Specification and Design of Real-Time Systems

Lecture 7:
Real-Time I/O, Partitioning, and Memory

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Outline

- Quiz (15 min)
- Lecture: I/O + Memory (35)
- Lab Exercise: vxWorks Memory (20)
- Project Work (40)
- Exam Makeup Questions (60)

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Issues

- Input / Output (I/O) concept and operations
- Communicating with devices
- Memory types
- Partitioning and protection
- Memory management
- Shared memory
- Memory allocation and fragmentation
- Memory in VxWorks
- Memory problems

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Input-Output (I/O) Subsystem

- Variety of I/O devices require non-conventional device drivers
- I/O operations paradigm:
  - Communicate with device
  - Initiate I/O request
  - Transfer data
  - Notify operation completion
- Software engineer must understand the physical properties (register definition, operations, access method)
- The I/O incorporates all issues real-time software developer must face (timing, concurrency, synchronization, communications, interrupts)

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Basic I/O Concepts

- I/O device hardware may include serial, network, wireless, hard drives, scanners, sensors, actuators, etc.
- From programmer viewpoint, each device is represented as set of registers that need to have specific address to allow for an access
- **Port-Mapped** vs. **Memory-Mapped** I/O:
  - There may be separate I/O address space or devices will have dedicated system address space
- **Character** Mode vs. **Block** Mode:
  - Data transfer can occur one character at a time or as entire block of data

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Basic I/O Refresher

- Devices are defined by a file descriptor *fd* which is a small integer returned by *open()* or *create()*
- The created device (or file) is opened:
  - *fd = open ("name", flags, mode);*
  - Flags and mode are defining read/write features and permissions
- We read data from *fd* to the *buffer*:
  - *nBytes = read (fd, &buffer, maxBytes);*
- We write data to *fd* from the *buffer*:
  - *write (fd, &buffer, nBytes);*
- The buffer must be allocated first:
  - *buffer = malloc(maxBytes);*

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Basic I/O Operations

- Sequence of operations:
  - Communicating with device
  - Programming device to initiate I/O request
  - Actual data transfer
  - Notification of completion
- Seven basic I/O calls:
  - *create( )* - create a file/device
  - *remove( )* - remove a file/device
  - *open( )* - open a file/device (sometimes used to create)
  - *close( )* - close a file/device (sometimes used to delete)
  - *read( )* - read previously created or opened file/device
  - *write( )* - write previously created or opened file/device
  - *ioctl( )* - perform special control functions on file/device

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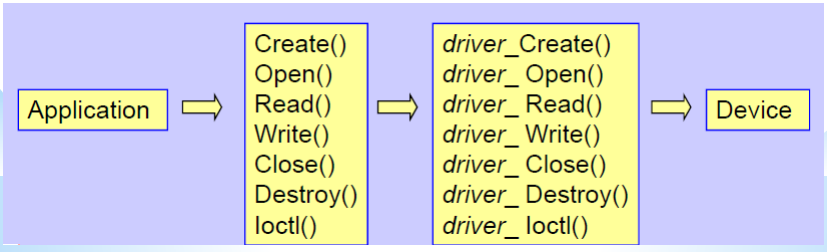
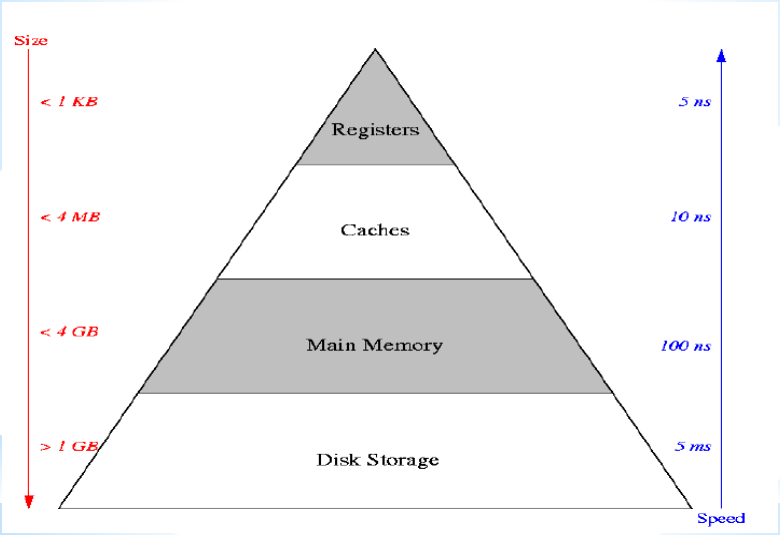
Mapping I/O Calls to Driver Calls

- The individual device driver provides implementation of basic I/O functions in a uniform API set
- The kernel driver table associates the devices with the device drivers (e.g. *driver* can be ***tty***, ***fei***, ***fd*** …)
- Mapping is initializing each generic I/O function pointer with the device specific address of driver function
- The record is kept in I/O driver table with entries created when driver is installed



Memory Hierarchy



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What is Partitioning?

- Idea: to prevent undesirable interference between software components
- **Partitioning** is a functional separation of the applications
- Used primarily for fault containment: to prevent any partitioned application from causing a failure in another partitioned application
- **Partition** is a unit of partitioning, i.e. an equivalent of a stand-alone program in single application environment, consisting of data context related devices and data, context, related devices, configuration attributes
- However, we may need to establish multiple functional partitions within one program

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Why do we need partitioning?

- Increasing interactions in the integrated embedded systems architectures
- ***Fault containment is the main objective of partitioning***
- The goal is to control the hazards created when a function shares resources with other functions
- Protection from loss of function is addressed by redundancy

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Partitioning Options (1)

- **Physical partitioning** (in hardware):
  - involves the allocation of software components to hardware based on the hazard level of the components (only components of identical or similar hazard levels)
- **Logical partitioning** (in software):
  - used when physical partitioning is not possible
  - it requires the identification and appropriate protection of all resources that the software component may share with any other software component (examples?)

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Partitioning Options (2)

- **Spatial partitioning** (in location):
  - to ensure that software in one partition cannot change the software or data of another partition, nor command the private devices or actuators of other partitions.
- **Temporal partitioning** (in time):
  - to ensure that the service received from shared resources by the software in one partition cannot be affected by the software in another partition (including rate, latency, duration, jitter)

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Spatial Partitioning Issues

- Communication – kernel executes copy from a buffer in one partition to another
  - An alternative might be a single buffer allocation that one partition can write and another read
  - Bi-directional buffer might be acceptable, but a separate buffer is required for each partition pair
  - Restrict unnecessary ***direct*** communication
- Naming conventions for partition address:
  - Absolute (e.g. partition A) – too rigid and limiting
  - Functional (e.g. Autopilot) – limits possible reconfiguration
  - Relative (e.g. port 13) – allows binding

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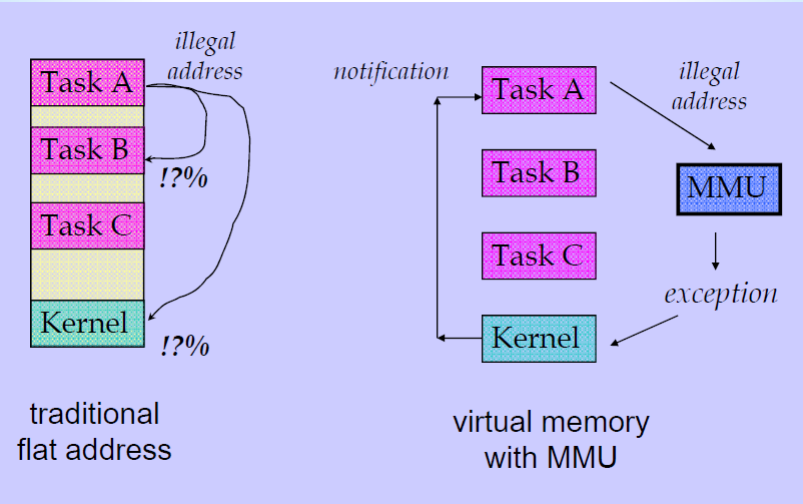
Example: Spatial Protection



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Temporal Partitioning Issues

- Concerns: monopolizing processor, halting processor, schedule overruns
- Runaway execution may be prevented by using ???
- but the other partitions may still be doomed (Example?)
- Notification of failure is required

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Memory Management: Observations

- Task must be in main memory to be executed
- Task may be swapped (rolled) in/out of main memory
- Only idle task can be swapped
- Swapping generally not a good idea for – real-time (Why?)

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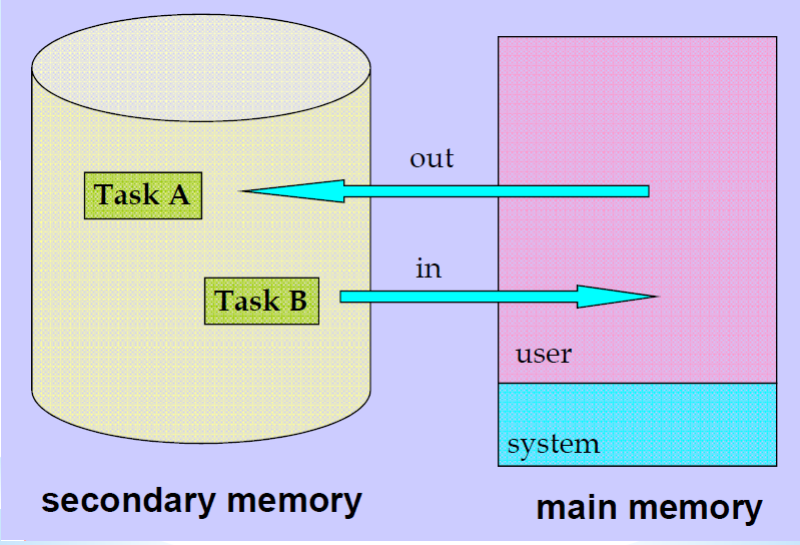
Example: Memory Swapping



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Memory Management (MM) Approaches

- **Hardware MM** – concerned with the physical devices storing data including the access to ROM and processor cache
- **Operating System MM** – handling the allocation of memory to application programs and the translation between the virtual and physical memories
- **Application MM** – involves allocation and de-allocation of memory to the programming constructs (buffers, queues, data structures)

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Shared Memory - Basics

- Shared memory and memory mapping are extremely low level communication mechanisms
- They require great deal of synchronization to be implemented within the application (mutex, semaphore, condition variable, monitor)
- The advantage is great speed – the processes "see" the memory immediately
- POSIX_SHARED_MEMORY_OBJECTS option is required (see unistd.h)
- Additionally, _POSIX_MAPPED_FILES and _POSIX_SYNCHRONIZED_IO are required to use memory mapping and synchronization

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Shared Memory - Operations

- Shared memory object is constructed like a file pathname with an absolute path, and opened with *shm_open()* returning an integer file descriptor
  - *int shm_open(const char *shmname, int oflag, mode_t mode);*
- To set the size of the memory block we use confusing function name *ftruncate()* both to shrink and lengthen the memory
- We use *close()* to remove the shared memory objects and reclaim memory
- We use *mmap()* and *munmap()* to associate and disassociate memory with a process
- Memory protection defines permission for mapping: it must reflect the status of flags used to open the shared memory segment

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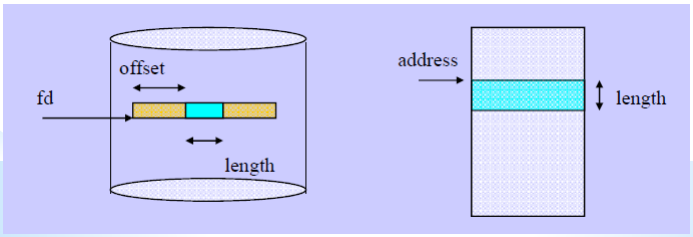
Shared Memory - Use

- To get the created shared memory block into the address space of the process we need to map the descriptor using *mmap()*
- *void * mmap(void *address, size_t length, int protection, int flags, int fd, off_c offset);*
- The system controls the actual assignment and returns the address afterwards
- Once memory address is known, it can be used for all subsequent shared memory allocations



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Dynamic Memory Allocation

- Memory is broken into fixed size blocks
- Memory area control block retains information on:
  - starting address
  - overall size
  - allocation array (indicating areas used/free)
- Dynamic allocation is using **heap** data structure to facilitate speed-up the search for free blocks
- In Groups: What is internal fragmentation?
- What is external fragmentation?

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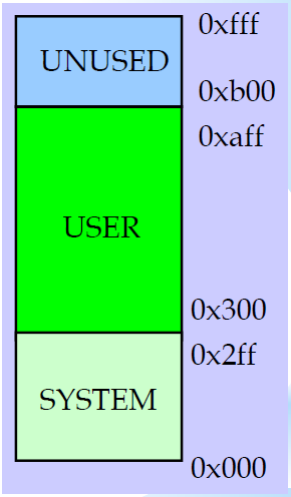
Memory Map

- Memory is partitioned into two parts:
  - operating system
  - user tasks
- The user tasks may be in:
  - a single partition
  - multiple partitions
- Protection by watching the access address



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Multiple Partition: Fixed Allocation

- Memory divided into fixed size partitions
- When partition is free a task can be loaded
- When task terminates the partition is freed
- The memory manager keeps track of empty partitions
- What kind of system is this good for?

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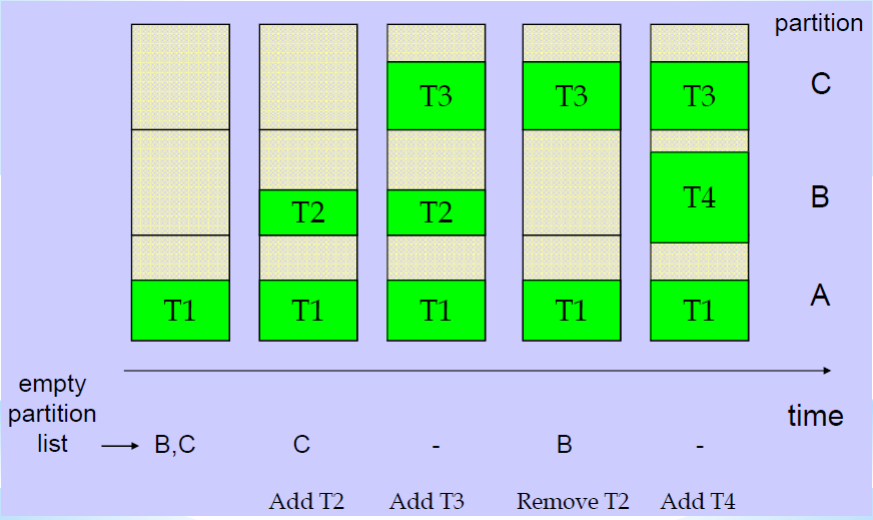
Example: Fixed Allocation



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Multiple Partition: Dynamic Usage of Statically Allocated Memory

- Initially all memory is available
- New task requests specific memory space
- Memory is assigned in increasing order
- Removal of task creates an empty partition
- The memory manager keeps track of empty partitions (holes) and allocates memory using placement algorithm as:
  - First-fit – the first hole big enough
  - Best-fit – the smallest hole available

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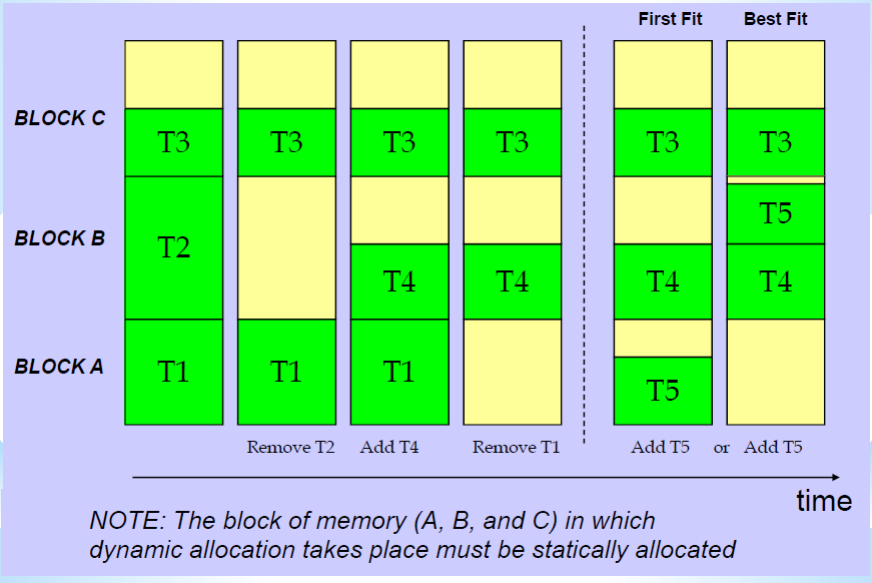
Example: Dynamic Allocation



NOTE: The block of memory (A, B, and C) in which dynamic allocation takes place must be statically allocated

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vxWorks Memory Operations

- To dynamically allocate memory: ***void *malloc (nBytes)***
  - Returns a pointer to the allocated memory or *NULL*
  - Uses first-fit algorithm
  - Free memory is stored in a linked list
  - Some (small) overhead for each ***malloc( )***
- To release allocated memory: ***void free (ptr)***
  - Adjacent blocks are merged
- To resize allocated block ***void *realloc (ptr, newSize)***
- To returns size of the largest free block in system memory ***int memFindMax( )***

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Generic Partition Manager

- VxWorks provides low-level routines to create and manipulate alternate memory pools
- High-level routines like ***malloc( )*** and ***free( )*** call these lower level routines, specifying the system memory pool
- Application may use alternate memory partitions to reduce fragmentation
- Application may use alternate memory partitions to manage memory with different properties

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Creating and Managing a Memory Partition

will do an example in lab exercise

- ***PART_ID memPartCreate (pPool, size)***
  - ***pPool*** Pointer to memory for this partition
  - ***size*** Size of memory partition in bytes
- Returns a partition ID *(**PART_ID**)*, or *NULL* on error
- System partition management routines call routines listed below, specifying the ***PART_ID*** as ***memSysPartId***

Generic	System Memory Pool
memPartAlloc( )	*malloc( )*
memPartFree( )	*free( )*
memPartShow( )	*memShow( )*
memPartAddToPool( )	*memAddToPool( )*
memPartOptionsSet( )	*memOptionsSet( )*
memPartRealloc( )	*memRealloc( )*
memPartFindMax( )	*memFindMax( )*

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Memory Management Problems

In groups

- **Memory Leak**
  - when a task continually allocates memory (without proper de-allocation)
- **External Fragmentation**
  - poor allocation and the free memory blocks are too small to accommodate requests
- **Dangling Pointer**
  - a task de-allocates memory but attempts to access it later
- **Poor Locality**
  - the blocks of memory allocated far apart causing performance problems
- **Inflexible Design**
  - different view of memory type of use between memory manager and application
- **Interface Complexity**
  - when data objects are being passed between modules
- **Memory Exhaustion**
  - when a repeated request for service or a growing log depletes memory

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Summary

- Standard C routines are used for dynamic memory allocation
- To configure the system memory pool:
  - Modify *LOCAL_MEM_SIZE* in ***config.h***
  - Specify *USER_RESERVED_MEM*
  - Call ***memAddToPool( )***
- For fast, deterministic allocation of fixed size buffers,
  - use message queues instead of ***malloc( )***
- Create separate memory partition for off-board memory, or to help reduce fragmentation

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vxWorks Memory in-class lab

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