# OS?

## Based on

*Embedded Systems: A Contemporary Design Tool*
James Peckol

and
*EE472 Lecture Notes Pack*
Blake Hannaford, James Peckol, Shwetak Patel

# Why would anyone want an OS?

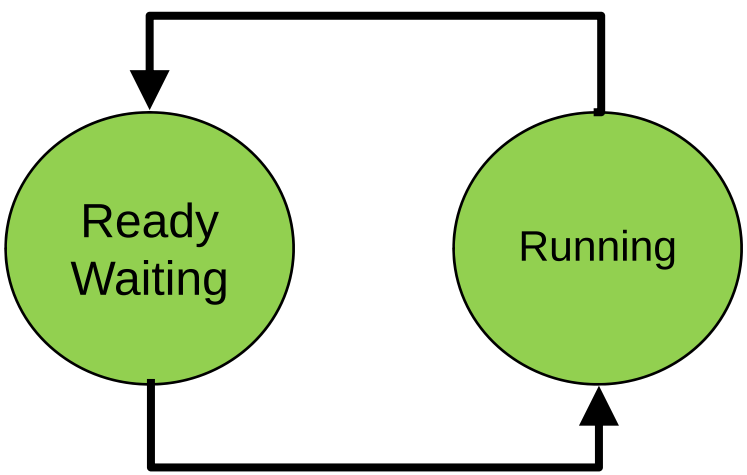
- Goal: run multiple programs on the same HW "simultaneously"
  - i.e. multi-tasking…it means more than surfing Facebook during lecture
- Problem: how to share resources & avoid interference
  - To be shared: processor, memory, GPIOs, PWM, timers, counters, ADCs, etc
  - In embedded case, we may need to do the sharing while respecting "real time" constraints

- OS is responsible for ***scheduling*** the various jobs

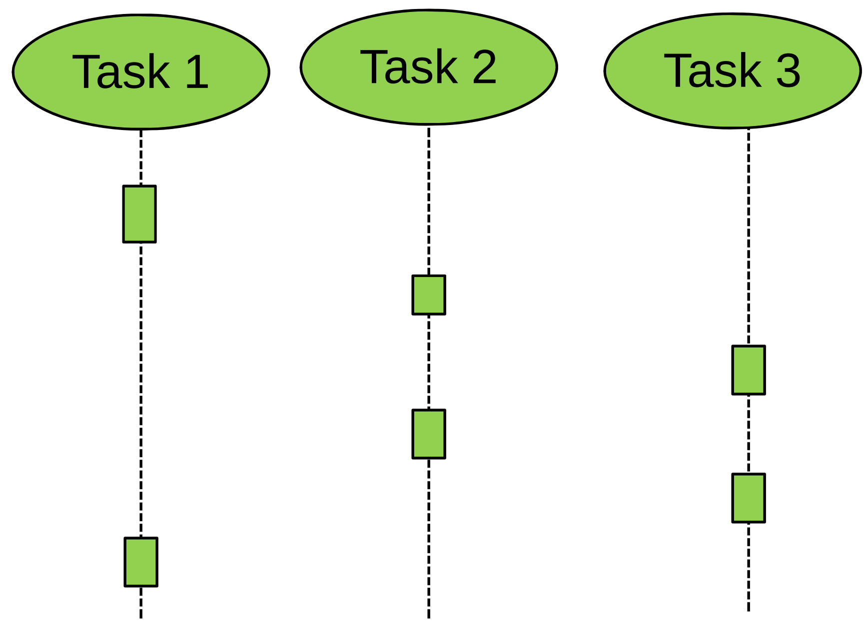
- Also:
  - OS provides abstractions of HW (e.g. device drivers) that make code more portable & re-usable, as well as enabling sharing
  - Code re-use a key goal of ROS ("meta-operating system")
  - Power: maintain state across power loss, power aware scheduling

# Tasks / Processes, Threads

- Task or process
  - Unit of code and data… a program running in its own memory space
- Thread
  - Smaller than a process
  - A single process can contain several threads
  - Memory is shared across threads but not across processes




With just 1 task, it is either Running or Ready Waiting



# Types of tasks

- Periodic --- Hard real time
  - Control: sense, compute, & generate new motor cmd every 10ms
  - Multimedia: sample audio, compute filter, generate DAC output every 22.73 uS
  - Characterized by
    - P, Period
    - C, Compute time (may differ from instance to instance, but C<=P)
    - D, Deadline (useful if start time of task is variable)
      - C < D < P
- Intermittent
  - Characterized by
    - C and D, but no P
- Background
  - Soft realtime or non-realtime
  - Characterized by
    - C only
- Complex
  - Examples
    - MS Word, Web server
  - Continuous need for CPU
  - Requests for IO or user input free CPU

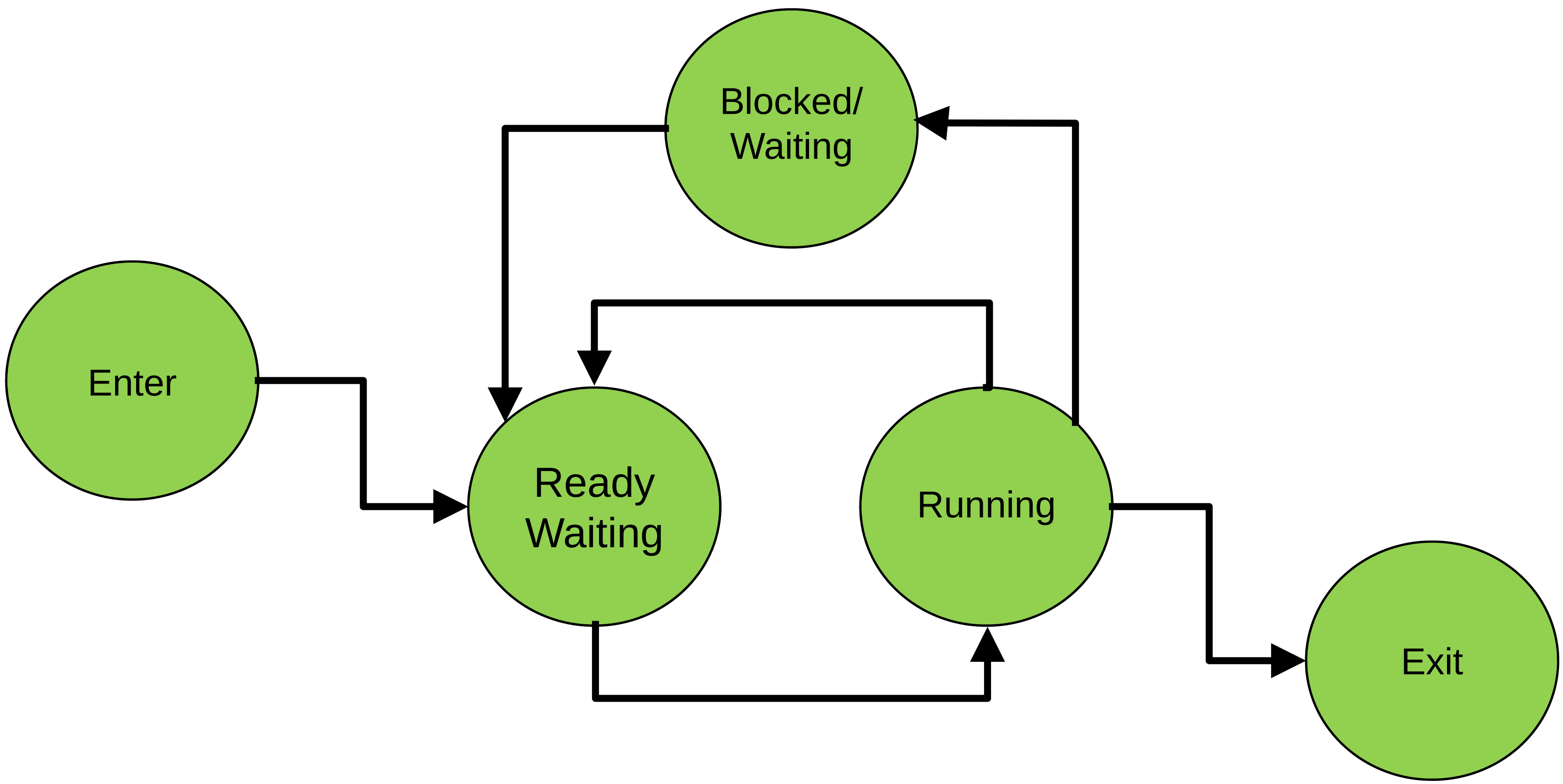
# Scheduling strategies

- Multiprogramming
  - Running task continues until a stopping point (e.g. waiting for an IO event)
- Real-time
  - Tasks must be completed before deadline
- Time sharing
  - Running task gives up CPU
  - Cooperative multitasking
    - App voluntarily gives up control
      - Old versions of Windows & Mac OS
      - Badly behaved apps hang the system
  - Preemptive multitasking
    - HW timer ***preempts*** currently executing task, returns control to OS
      - All versions of Unix
- Power aware
  - Research topic

# Context

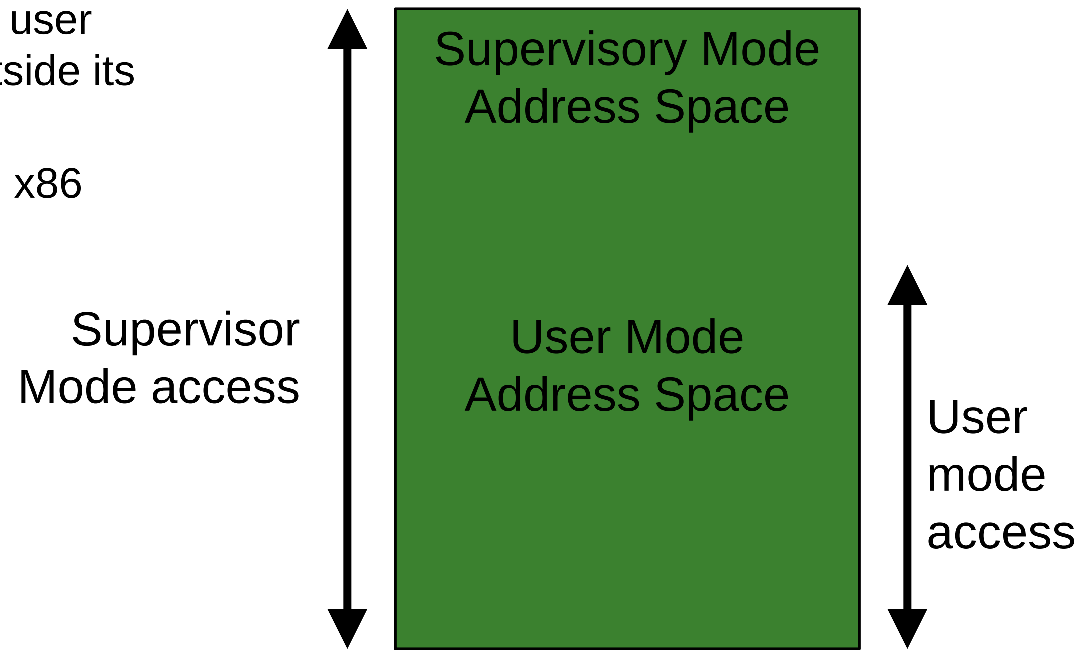
- State must be saved / restored to switch between tasks
  - Program Counter (PC)
  - Register values
  - Processor status flags (Status Register)
  - Stack Pointer (SP)
  - Memory state
  - Peripheral configurations
  - Etc

# Task states in a time-sharing system



# Memory resource management

- Address space
  - Each process has a range of addresses it's allowed to use
- Privilege level
  - Supervisory / kernel mode
  - User mode
    - Interrupt generated when a user process tries to operate outside its address space
    - "General protection fault" in x86



# Task Control Block (TCB)

| Task Control Block |
| --- |
| Pointer |
| State |
| Process ID |
| Program Counter |
| Register contents |
| Memory limits |
| Open Files |
| Etc. |

Also: scheduling information, memory management information, I/O status info

# Task Control Block (TCB)

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

taskPtr is a pointer to a function

The function's param list has one arg, of type void*

stackPtr: each task has its own stack

Priority: what is the priority level of this task?

nextPtr & prevPtr: pointers to other TCBs

# Scheduling

# Time (for RTOS)

- Time slice T, Ticks
- $P_{min}$, shortest period of all tasks in system
- $T < P_{min}$, sometimes $T << P_{min}$

# Scheduling goals

- CPU Utilization
  - $U_{CPU}$ = 1 – idle / period
  - In mainframe, 100% is best, but 100% not safe for realtime systems
  - Goal: 40% low load, 90% high load
- Throughput
- Turnaround time
- Waiting time
- Response time

# Scheduler types

- Infinite loop, aka non-preemptive Round Robin

```
while(1) {
        task1_fn();
        task2_fn();
        task3_fn();
}
taskN_fn() {
        compute a little bit;
        return();
}
```

# Scheduler types

- Synchronized Infinite loop
  - Top of loop waits for a HW clock

```
while(1) {
        wait(CLOCK_PULSE);
        task1_fn();
        task2_fn();
        task3_fn();
}
```

# Scheduler types

- Preemptive round robin
  - AKA cyclic executive
  - All processes handled without priority
  - Starvation free

# Scheduler types

- Preemptive priority based
  - Goal in non-RT OS is to allocate resources equitably…no process should perpetually lack necessary resources
  - Attach priorities to each process
    - Problem: priority inversion
      - A is highest priority process. It is blocked waiting for a result from C
      - B is $2^{nd}$ highest priority. It never blocks
      - C is $3^{rd}$ highest priority
      - Now B runs all the time and A never gets to…their priorities are effectively inverted…A is starved
    - Problem: deadlock
      - Catch 22 / Chicken - Egg: A is waiting for B, but B is waiting for A
      - One person has the pencil but needs the rule, the other has ruler but needs pencil
      - You can't make coffee until you're alert…but you're not alert until you've had coffee
  - Ways to avoid priority inversion
    - Make sure every job gets a minimum time slice
    - Priority inheritance
      - Does not prevent deadlock when there are circular dependencies

# Scheduler types

- Preemptive priority based
  - Rate monotonic scheduling (RMS), for RTOS
    - Static priorities set based on job cycle duration---shorter job gets scheduled more often
    - Provide deterministic guarantees about response times (show using Rate Monotonic Analysis)

$$U = \sum_{i=1}^{n} \frac{C_i}{T_i} \leq n(2^{1/n} - 1)$$

Where
Ci is compute time
Ti is release period
n is # processes to be scheduled

$$\lim_{n \to \infty} n(\sqrt[n]{2} - 1) = \ln 2 \approx 0.693147\ldots$$

Roughly, RMS can meet deadlines when CPU < 69% used

# End

# Real-Time OSes and their communities

- Linux
  - RTLinux
  - RTAI
  - Xenomai
- Commercial
  - LynxOS
  - QNX
  - VxWorks
  - Windows CE
  - iRMX for Windows
  - OSE
- Embedded systems
  - FreeRTOS
  - µC/OS-II
- Sensor networks
  - TinyOS
  - Contiki
- Computational RFID
  - Dewdrop
  - MementOS
- Robotics [“meta OSes,” on top of Linux]
  - ROS
  - Player / Stage
  - Carmen

# RTLinux

- Hard realtime RTOS microkernal runs entire Linux OS as a preemptive process
- Real time OS is virtual machine “host OS” …Linux kernal runs as “guest OS”
- Interrupts for realtime processing handled by realtime core
- Other interrupts forwarded to Linux, handled at lower priority than realtime interrupts
- Acquired by WindRiver, sold as Wind River Real-Time Core for Wind-River Linux

# RTAI & Xenomai (Real time Linux)

- RTAI==Real Time Application Interface
  - Provides deterministic response to interrupts
  - Kernel patch allows RT system to take over key interrupts, leaves ordinary Linux to handle others
  - No patent restrictions (vs RTLinux)
  - Lowest feasible latencies
- Xenomai
  - Emphasizes extensibility rather than lowest latency

# μC/OS-II

- www.ucos-ii.com
- Kernal only…supports
  - Scheduling
  - Message passing (mailboxes)
  - Synchronization (semaphores)
  - Memory management
  - Supports 64 priority levels…runs highest priority first
  - Does not support: IO devices, Files, networking
- Versions
  - mC/GUI
  - mC/USB-Bulk
  - mC/USB-MSD [for Mass Storage Devices]

# FreeRTOS

- http://www.freertos.org/
- Another realtime kernal
- Many features similar to μC/OS-II
- Supports both tasks and *co-routines*
  - A co-routine does not have its own stack
  - Smaller memory footprint, more efficient
  - Restrictions on how/when to call etc required
- Versions
  - OpenRTOS
    - Commercial, supported
  - SafeRTOS
    - Documented for safety critical applications

# Contiki and TinyOS

- See Contiki slides
- More info:

http://www.sics.se/contiki/wiki/index.php/Main_Page

# DewDrop

- Energy-aware runtime (scheduler) for computational RFID
- Interesting to compare power aware scheduling to RTOS ("time-aware scheduling")

# ROS

- Robot Operating System
  - Meta-operating system
- See
  - ros_overview.pdf
  - ros_tutorial.pdf

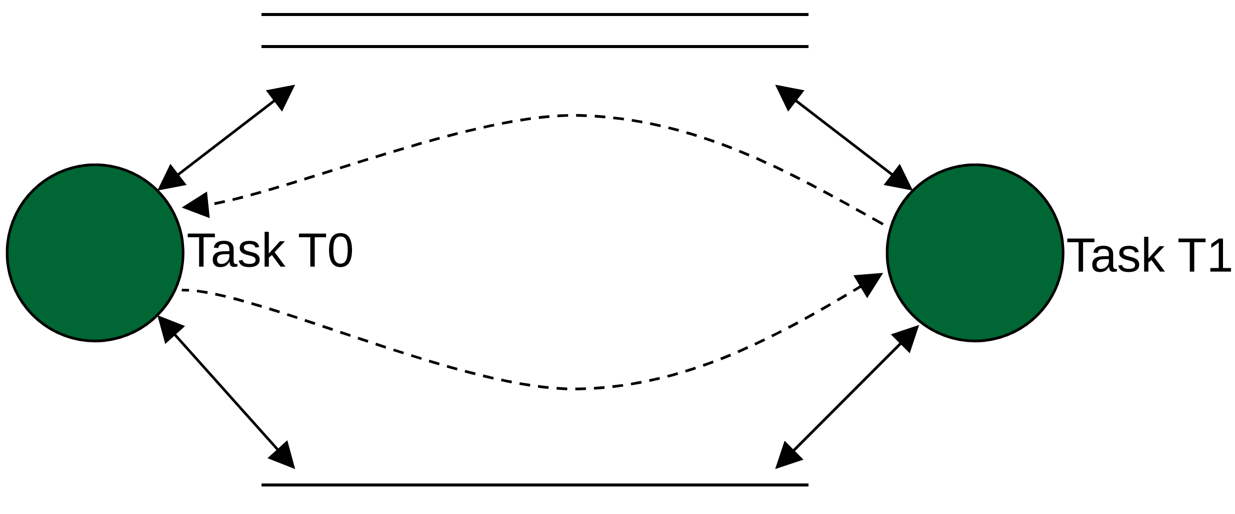
# Inter-task communication

- Shared variables
  - Global variable
  - Shared buffer: producer & consumer


Problems: mismatch in filling & emptying rates can lead to over- or underflow
Solution: always check empty / full before reading / writing

# Inter-task communication

- Shared variables
  - Shared double buffer (ping pong buffer)

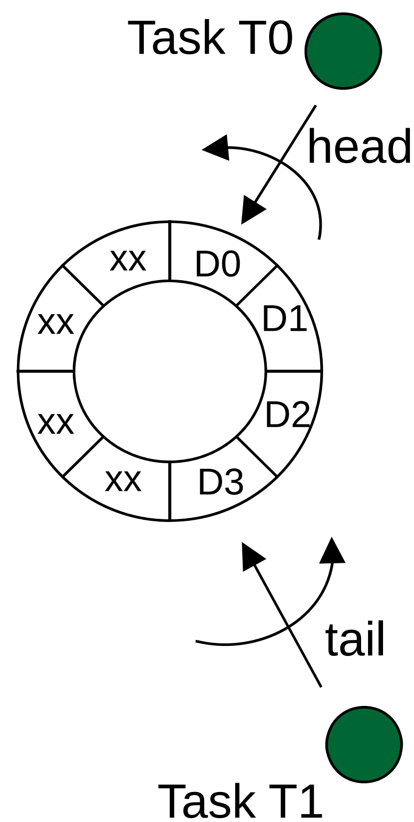



One buffer is being filled while the other is being emptied (also used for displays / graphics!)

Can generalize to n buffers…may be useful when producer generates data in fast short bursts

# Inter-task communication

- Shared variables
  - Ring buffer
    - An implementation of a queue, used to let 2 processes communicate
    - FIFO (First In First Out)
    - Need to avoid under/overflow



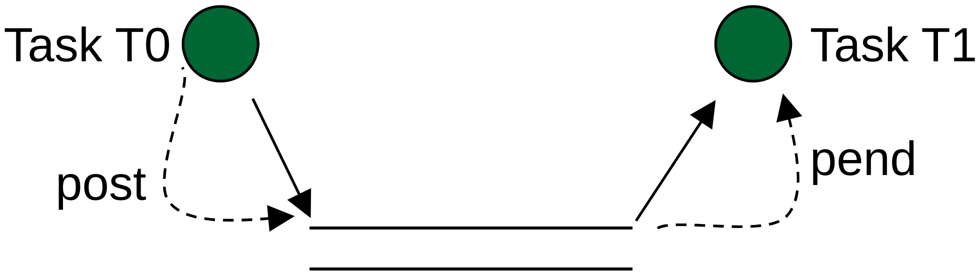

D0 – D3: valid data
xx: junk

# Inter-task communication

- Shared variables
  - Mailbox

**Interface**

```
post(mailbox, data) // post to mailbox
pend(mailbox, data) // pend on mailbox
```




A flag indicates that data has been posted…reading clears flag
Variants: can implement as
a queue of length 1,
extensible queue (length n)
priority queue
A way to share a critical resources
Pend differs from poll since during pend, CPU can do other things

# Inter-task communication

- Messaging / communication
  - Generalize mailbox from “agreed-upon memory address accessed by defined interface” to more abstract address (which could be on another processor)
  - ➔ Inter-Process Communication (IPC)
    - send & receive instead of post & pend

# Inter-task communication

- Messaging / communication
  - Direct
    - `send (T1, message)  // send message to Task T1`
    - `receive (T0, message)  // receive message from Task T0`
  - Indirect
    - `send(M0, message) // send message to mailbox M0`
    - `receive(M0, message) // receive message from mailbox M0`
    - Multiple tasks may be able to read from / write to a mailbox

# Inter-task communication

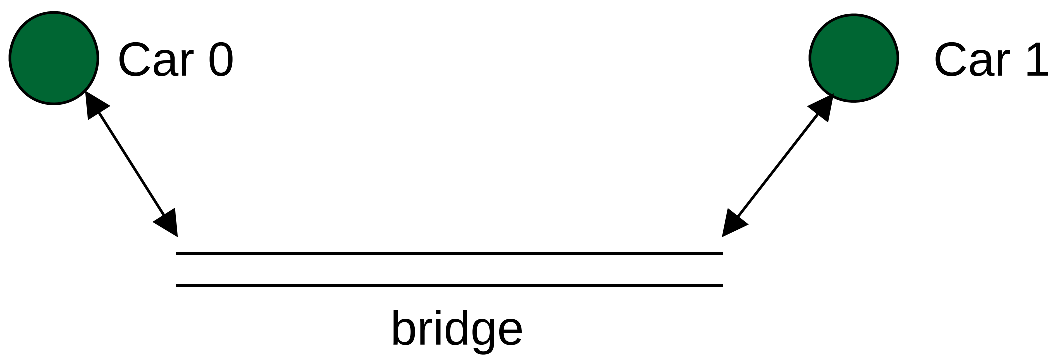
- Messaging / communication
  - Messaging systems can be buffered in 3 different ways
    - Link has 0 capacity ➔ *rendezvous* or *Idle RQ protocol*
      - RQ: “Repeat reQuest”
      - TX waits for RX to accept message [ACK, NACK, timeout]
      - AKA “stop and wait” or “synchronous”
    - Link has bounded capacity…queue length of n
    - Link has unbounded capacity ➔ *continuous RQ protocol*
      - TX never has to wait
      - TX can send next packet before receiving ACK from previous packets
      - AKA “asynchronous”
  - NB: Idle RQ and Continuous RQ are examples of “backward error correction” (BEC) protocols, which manage re-transmission when errors are detected. Contrast with Forward Error Correction (FEC), which we discussed earlier with error correcting codes [Hamming, LDPC, Raptor, etc]

# Task cooperation, synchronization, sharing

- Concurrent access to common data can result in data inconsistency, unexpected behavior, system failure
- Need to manage interactions of multiple tasks with common resources

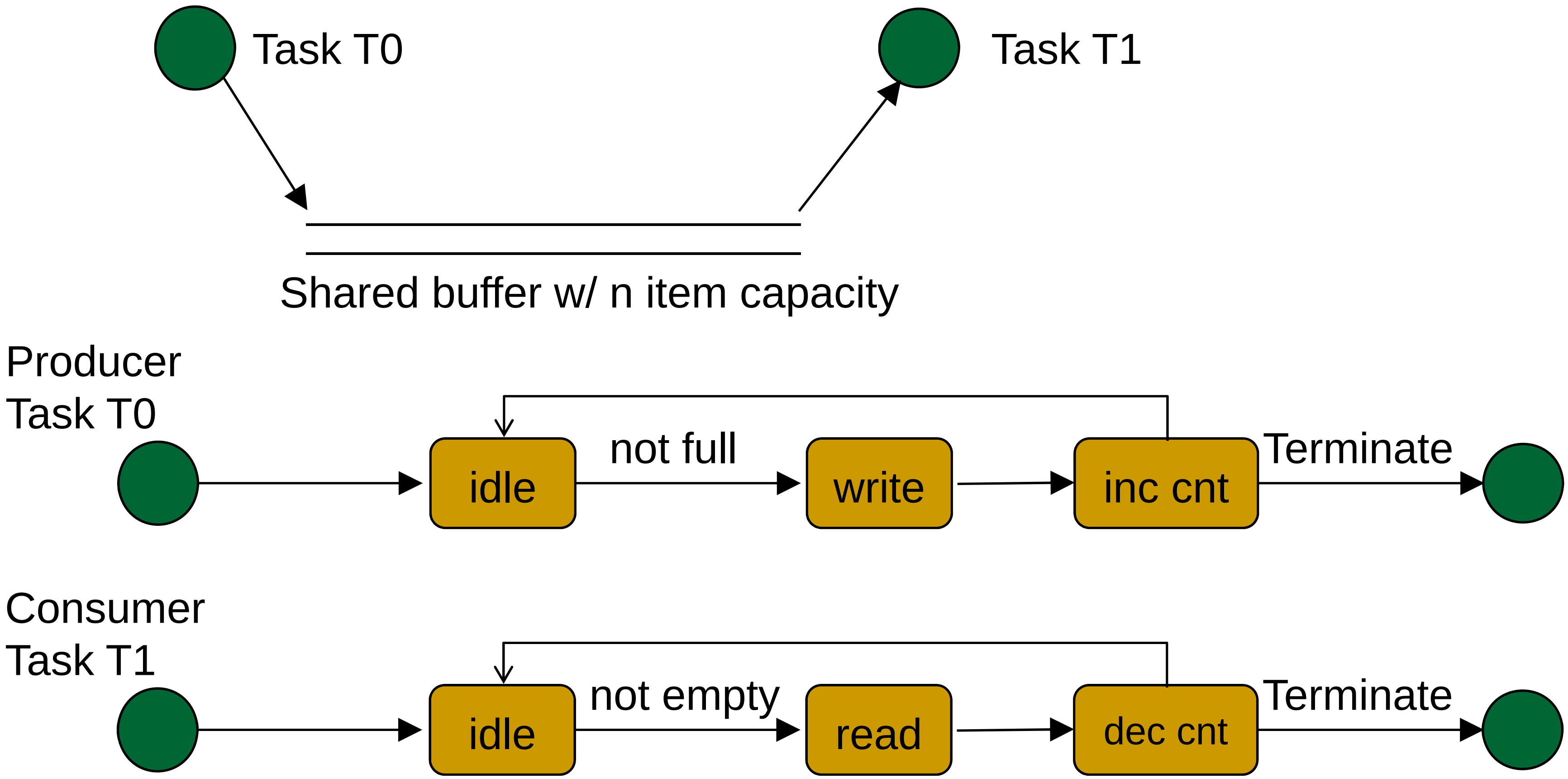
# Task cooperation, synchronization, sharing

- Bridge example
  - Critical section of roadway…can't be occupied by both cars at once
  - Need to manage access to shared resource to avoid collisions



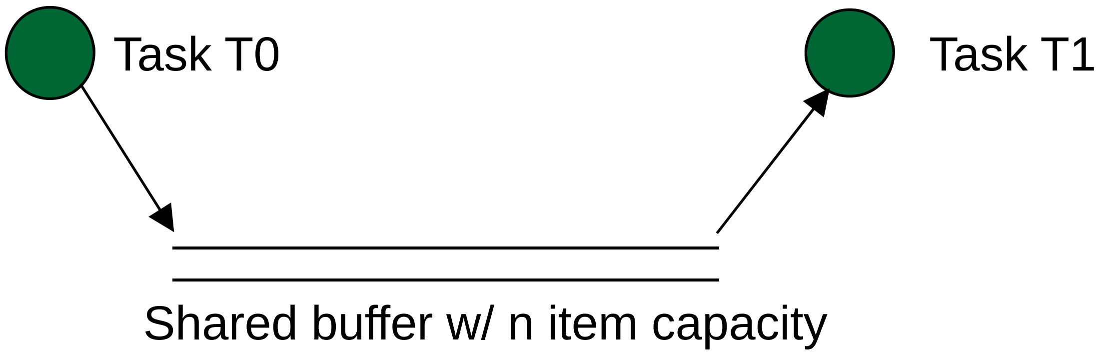
# Task cooperation, synchronization, sharing

- Example: N item buffer



# Task cooperation, synchronization, sharing

- Example: N item buffer




**<u>Task T0 --- Producer</u>**

```
while (1)
  if not full
    add item
    increment count
  else
    wait for space
end while
```

**<u>Task T1 --- Consumer</u>**

```
while (1)
  if not empty
    get item
    decrement count
  else
    wait for item
end while
```

***The variable*** `count` ***is a critical shared resource…its value can depend on how the two processes interleave at the lowest level…see next slide***

# Task cooperation, synchronization, sharing

- Example of problem

> "Race condition" --- result is determined by "which input gets to the output first"
>
> Any SW or HW situation in which result depends critically on timing

**count++** implementation:

**register1 = count**
**register1 = register1 + 1**
**count = register 1**

**count--** implementation:

**register2 = count**
**register2 = register2 - 1**
**count = register2**

Let count = 5 initially. One possible concurrent execution of count++ and count-- is

register1 = count {register1 = 5}
register1 = register1 + 1 {register1 = 6}
register2 = count {register2 = 5}
register2 = register2 - 1 {register2 = 4}
count = register1 {count = 6}
count = register2 {count = 4}

count = 4 after count++ and count--, even though we started with count = 5
Question: what other values can count be from doing this incorrectly?

***Problem is caused by inter-leaving of read & write operations on the same variable***

# Task cooperation, synchronization, sharing

- Example of non-problem

**count++** implementation:

**register1 = count**
**register1 = register1 + 1**
**count = register 1**

**count--** implementation:

**register2 = count**
**register2 = register2 - 1**
**count = register2**

Let count = 5 initially. One possible concurrent execution of count++ and count-- is

register1 = count {register1 = 5}
register1 = register1 + 1 {register1 = 6}
count = register1 {count = 6}
register2 = count {register2 = 6}
register2 = register2 - 1 {register2 = 5}
count = register2 {count = 5}
count = 5, the correct value

***This worked correctly because the operations modifying count were not interleaved***

# Task cooperation, synchronization, sharing

- How to prevent problems due to concurrent access to shared resources?
  - Ensure that access to shared resource is ***mutually exclusive***…only one process can access at time!
    - Mutual exclusion synchronization [locks]
    - Condition synchronization
  - Structure of a critical section

```
while(1)
  non-critical code
  entry section
  critical section
  exit section
  non-critical code
end while
```

# Task cooperation, synchronization, sharing

- Requirements to solve critical section problem
  - Ensure mutual exclusion in critical region
  - Prevent deadlock
  - Ensure progress through critical section
  - Ensure bounded waiting
    - Upper limit on the number of times a lower priority task can be blocked by a higher priority task

  - Definition: an *atomic operation* is guaranteed to terminate without being interrupted…all sub-steps comprising an atomic operation succeed or fail together

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Flags, embedded in an atomic operation

```
await (condition) { // await is "atomic wait"
  statements
} variable
```

Other tasks must be able to execute during `await`, otherwise deadlock can occur

Use `T0Flag` to mean Task 0 has lock; `T1Flag` means Task 1 has lock

```
await (!T1Flag) {T0Flag=True;}
await (!T0Flag) {T1Flag=True;}
```

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Flags

**count++** implementation:

  **register1 = count**
  **register1 = register1 + 1**
  **count = register 1**

**count--** implementation:

  **register2 = count**
  **register2 = register2 - 1**
  **count = register2**

**Task T0 --- Producer**

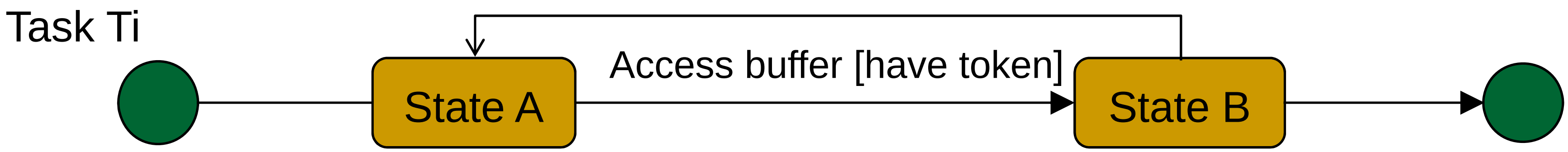
```
while (1)
  if not full
    add item
    await(!T1Flag){T0Flag=true;}
      count++
    T0Flag = false;
  else
    wait for space
end while
```

**Task T1 --- Consumer**

```
while (1)
  if not empty
    get item
    await (!T0Flag) {T1Flag=false;}
      count–
    T1Flag = false;
  else
    wait for item
end while
```

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Token passing: one token gets passed among tasks…only the task holding the token can access the resource




  - Problems:
    - Task holds on to token forever
    - Task with token crashes
    - Token lost or corrupted
    - Task terminates without releasing token
    - How to add new tasks?
  - Possible solutions?
    - Add a system task which manages token, and has watchdog timer
    - Getting complicated though

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Interrupt management
    - In a single processor system, disable interrupts in critical section
    - Similar problems to token passing: badly behaved code can screw up
    - Similar solutions: use a watchdog timer (with higher priority interrupt level, one that does not get disabled by critical section)

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Semaphores
    - Used to indicate availability of critical variable
    - Simplest example: boolean S with two atomic access operations
      - wait: P(S)   P from Dutch proberen, to test
        - wait tests semaphore value, and if false, sets to true
        - wait has two parts, test and set, which must occur together atomically
      - signal: V(S)   V from Dutch verhogen, to increment
        - sets value to false

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Semaphores

```
// implementation of semaphore
// notes: - wait must happen atomically!
//        - s should be initialized to false
wait(s) {
  while (s); // do nothing while another process has s set
  s = TRUE;  // now WE set s to be true to warn other processes
}

signal(s) {
  s = FALSE; // Turn off warning for other processes
}
```

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Semaphores

```
// use of semaphores

Task T0 {
  …
  wait(s)
  critical section
  signal(s)
  …
}

Task T1 {
  …
  wait(s)
  critical section
  signal(s)
  …
}
```

# Task cooperation, synchronization, sharing

- Mechanism for synchronization
  - Semaphores
    - Can also be used to enforce ordered execution of asynchronous tasks
    - Want f(x) to be called before g(y)
    - Use semaphore sync to do this

```
// semaphores for synchronization
sync = true // initialization

Task T0 {                    Task T1 {
  …                            …
  f(x)                         …
  signal(sync)                 wait(sync) // wait
  …                            g(y)
}                              …
                             }
```

Lock on critical section is called a *spin lock*, because T1 “spins” waiting for sync signal.  Other activity can occur on the system while T1 is waiting, but T1 is not accomplishing anything while waiting

# Task cooperation, synchronization, sharing

- Mechanisms for implementing mutual exclusion
  - Semaphores
    - Can be non-binary:  counting semaphores
    - Useful for managing a pool of identical resources
    - P and V, wait and signal, down and up, and other names used for semaphore access functions
    - vs Mutex [mutual exclusion]: same as binary semaphore, but
      - Mutex often has a notion of an “owner process” who must release mutex; semaphore usually has no owner

# Example messaging system: ROS

- See ROS slides

# ROS & multithreading in roscpp

- roscpp is the C++ implementation of ROS
  - roscpp provides a client library / API for C++ programmers
  - roscpp is the high performance option
  - vs rospy, python client library / API
- roscpp does not specify a threading model for apps

# Single threaded spinning: `spin()`

```
ros::init(argc, argv, "my_node");
ros::NodeHandle nh;
ros::Subscriber sub = nh.subscribe(...);
...
ros::spin();
```

- All user callbacks will be called from within `ros::spin()`
- `ros::spin()`does not return until node shuts down…instead, message handling events get processed

# Single threaded spinning: spinonce()

```
ros::Rate r(10); // 10 hz
while (should_continue)
{
   ... do some work, publish some messages, etc. ...
   ros::spinOnce();
   r.sleep();
}
```

- Call `ros::spinonce()` periodically
- `ros::spinonce()`calls all callbacks that are currently waiting to be processed
- Note: `spin()` and `spinonce()` are intended for single threaded apps

# Multi-threaded spinning: `MultiThreadedSpinner()`

```
ros::MultiThreadedSpinner spinner(4); // Use 4 threads
spinner.spin(); // spin() will not return until node
has been shutdown

```

similar

- Blocking spinner, similar to spin()
- You specify a number of threads
- Defaults to one thread per CPU core

# Multi-threaded spinning: `AsyncSpinner()`

```
ros::AsyncSpinner spinner(4); // Use 4 threads
spinner.start();
ros::waitForShutdown();
```

- This example is equivalent to previous blocking example
- Call to `start()` is non-blocking---execution returns right away
- In a real use, you'd put useful code after the `start()`, instead of immediately doing `waitForShutdown()`