“The race is not always to the swift, nor the battle to the strong, but that's the way to bet.”

– Hugh E. Keough
Anti-Patterns for Race Conditions:
- Unprotected access to shared variables
- Shared variables not declared volatile
- Not accounting for interrupts and task switching in timing analysis
- Ignoring non-reproducible faults

Race condition: multiple threads compete
- Computation outcome depends upon timing
  - Usually it is infrequent and hard to debug
- Concurrent access to shared variable
  - Need to lock shared resources
- Not accounting for multi-tasking
  - Task switch or interrupt causes delays
  - “Starvation” and priority inversion

Problems included:
- Operators “too fast” on keyboard (8 second window)
- Bypassed safety checks when counter rolled over to 0
Concurrency Management Bugs

- CPU switches among its tasks (multi-tasking)
  - What if switching happens at the wrong time?
- Concurrency bugs due to shared resources
  - Example: shared global variable, two tasks
    - Task 1 reads shared variable and computes new value
    - Task 2 preempts task 1, updates shared variable
    - Task 1 resumes, over-writing task 2’s update
  - Results of concurrency bug depend upon ordering
    - Usually bug won’t manifest (example: 9)
    - Sometimes bug will result in wrong value (example: 6, 8)
Easy solution for concurrency bug:

- Disable interrupts when touching shared variable
  - Inhibits task switches
  - But, need to keep it very brief to avoid timing problems

To hold resources longer, use a mutex

- "Mutual Exclusion" flag; True=busy / False=available
- To access shared resource:
  - Get the mutex (wait for it to be false, then set to true)
  - Access shared resource
  - Other tasks will wait while mutex is locked (resource busy)
  - When done, set mutex to false to release resource

- Mutexes are themselves a special type of shared variable
  - And therefore subject to race conditions!
  - Getting them right is tricky; let the RTOS do this for you
Minimize time interrupts are disabled
- Disabled task switching delays task switching
- **Blocking Time:** high priority tasks can miss deadlines

Mutexes indirectly cause blocking time
- **Priority Inversion:** low priority task blocks high priority task
  - Locked mutex prevents high priority task from making progress
  - Only affects tasks that actually use mutex, not all tasks
  - **BUT... there is a critical problem (next slide)**
Priority inversion can be unbounded for three tasks:
- Medium priority task blocks high task \textit{without ever touching mutex}:

Unbounded Priority Inversion

\begin{itemize}
\item High
\item Med
\item Low
\end{itemize}

\begin{itemize}
\item Normal Execution
\item \textit{M} Mutex Locked (Critical Section)
\item \textit{F} Fails To Get Mutex
\end{itemize}
Solution to unbounded priority inversion: **priority inheritance**

- Task priority elevated when locking mutex; restored when frees mutex
- This is complicated! Let the RTOS handle it

**Priority Inheritance**

**Bounded Priority Inversion**

- **Low**: Hoisted
- **High**
- **Med**
- **Low**

**Normal Execution** | **M** Mutex Locked (Critical Section) | **F** Fails To Get Mutex

**Time**
Mars Pathfinder Incident

- **July 4, 1997 – Pathfinder lands on Mars**
  - First US Mars landing since Vikings in 1976; first rover

- **But, a few days later…**
  - Multiple system resets occur via VxWorks RTOS
    - Watchdog timer saves the day! Sets system to safe state
    - Reproduced on ground; patch uploaded to fix it
  - Scenario pretty much identical to High/Medium/Low priority picture
    - Developers didn’t have Priority Inheritance turned on!
    - Why? “The data bus task executes very frequently and is time-critical -- we shouldn't spend the extra time in it to perform priority inheritance” [Jones07]

https://goo.gl/W5wHrU
Best Practices Avoiding Race Conditions

- Always consider task interactions
  - What if task switches at a bad time?
  - What if tasks read data at different times?
  - What if half-formed data structure is read?
  - What if multiple writers compete for data?
  - Use RTOS services to help

- Pitfalls:
  - Failing to use interrupt masking or mutexes
    - Failing to deal with unbounded priority inversion
    - Failing to declared shared variables volatile
  - Assuming that non-reproducible problems aren’t bugs
  - Trying to write your own bullet-proof concurrency services

18-348 Lecture explaining mutex operation at: https://goo.gl/wH9Q44