EECS 3215

“Software Design”

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The Architecture for the Digital World®

ARM

Material Source

ARM University
Worldwide Education Program

ARM-based Embedded Systems Design Lab-in-a-Box
Freescale Freedom Board Edition

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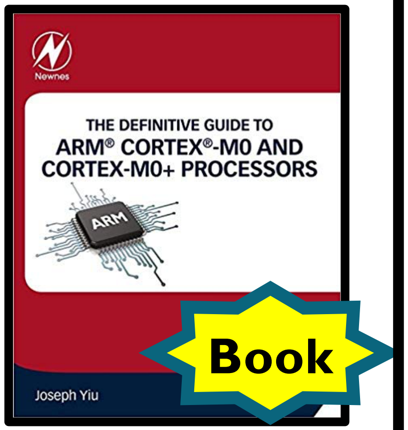
Material relevant to this class



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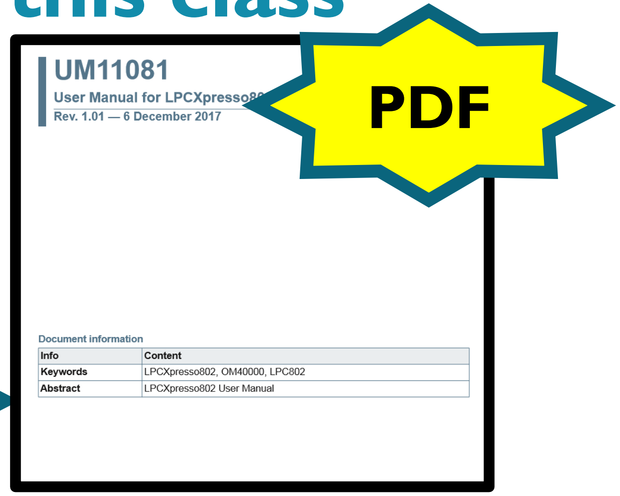

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Overview

- Software Engineering for Embedded Systems
  - How do we develop working code quickly & properly?
- Concurrency (Operating Systems & Schedulers)
  - How do we make things happen at the right times?

SOFTWARE ENGINEERING FOR EMBEDDED SYSTEMS

Good Enough Software, Soon Enough

- How do we make software *correct enough* without going bankrupt?
  - Need to be able to develop (and test) software efficiently
- Follow a good plan
  - Start with customer requirements
  - Design architectures to define the building blocks of the systems (tasks, modules, etc.)
  - Add missing requirements
    - Fault detection, management and logging
    - Real-time issues
    - Compliance to a firmware standards manual
    - Fail-safes
  - Create detailed design
  - Implement the code, following a good development process
    - Perform frequent design and code reviews
    - Perform frequent testing (unit and system testing, preferably automated)
    - Use revision control to manage changes
  - Perform post-mortems to improve development process

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What happens when the plan meets reality?

- We want a robust plan which considers likely risks
  - What if the code turns out to be a lot more complex than we expected?
  - What if there is a bug in our code (or a library)?
  - What if the system doesn't have enough memory or throughput?
  - What if the system is too expensive?
  - What if the lead developer quits?
  - What if the lead developer is incompetent, lazy, or both (and *won't* quit!)?
  - What if the rest of the team gets sick?
  - What if the customer adds new requirements?
  - What if the customer wants the product two months early?

- Successful software engineering depends on balancing many factors, many of which are non-technical!

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Risk Reduction

- Plan to the work to accommodate risks
- Identify likely risks up front
  - Historical problem areas
  - New implementation technologies
  - New product features
  - New product line
- Severity of risk is a combination of likelihood and impact of failure

Software Lifecycle Concepts

- Coding is the most visible part of a software development process but is not the only one

- Before we can code, we must know
  - What must the code do? *Requirements specification*
  - How will the code be structured? *Design specification*
    - *(only at this point can we start writing code)*

- How will we know if the code works? *Test plan*
  - Best performed when defining requirements

- The software will likely be enhanced over time - *Extensive downstream modification and maintenance!*
  - Corrections, adaptations, enhancements & preventive maintenance

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Product Development Lifecycle

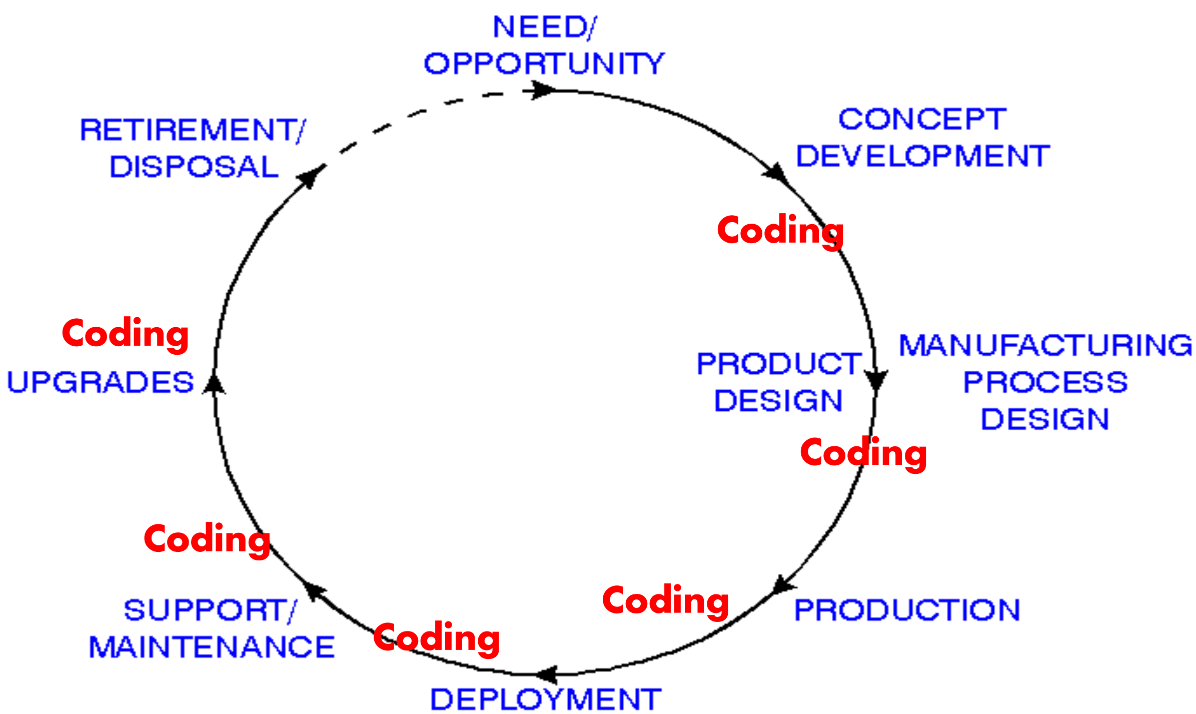

Diagram: Phil Koopman, Carnegie Mellon University

- With all this code development and modification, it is worth putting extra effort into simplifying code development activities: understanding, maintaining, enhancing, testing

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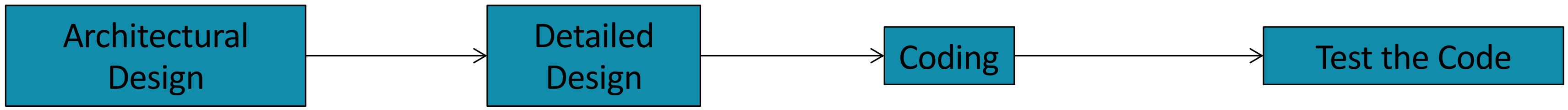
Requirements

- Ganssle's Reason #5 for why embedded projects fail: ***Vague Requirements***
- Types of requirements
  - Functional - what the system needs to do
  - Nonfunctional - emergent system behaviors such as response time, reliability, energy efficiency, safety, etc.
  - Constraints - limit design choices
- Representations
  - Text – Liable to be incomplete, bloated, ambiguous, even contradictory
  - Diagrams (state charts, flow charts, message sequence charts)
    - Concise
    - Can often be used as design documents
- Traceability
  - Each requirement should be verifiable with a test
- Stability
  - Requirements churn leads to inefficiency and often "recency" problems (most recent requirement change is assumed to be most important)

Jack Ganssle's "top 10 reasons for failure": http://www.ganssle.com/articles/jackstoptenlist.htm

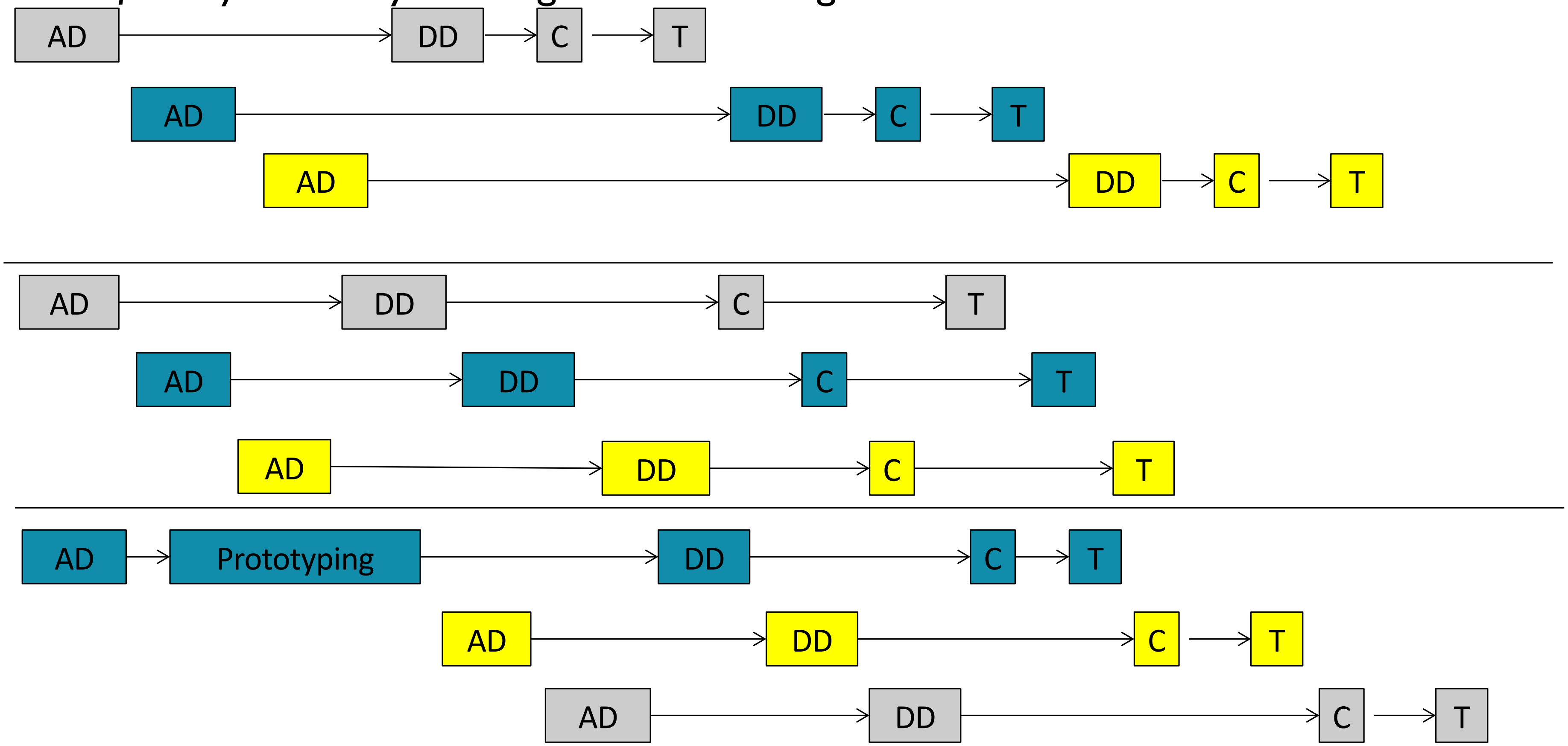
Design Before Coding



- Ganssle's reason #9: ***Starting coding too soon***
- Underestimating the complexity of the needed software is a very common risk
- Writing code locks you in to specific implementations
  - Starting too early may paint you into a corner
- Benefits of **designing** system before **coding**
  - Get early insight into system's complexity, allowing more accurate effort estimation and scheduling
  - Can use design diagrams rather than code to discuss what system should do and how. Ganssle's reason #7: ***Bad Science***
  - Can use design diagrams in documentation to simplify code maintenance and reduce risks of staff turnover

Design Before Coding

- *How much of the system* do you design before coding?



Development Models

- How do we schedule these pieces?

- **Consider** amount of **development risk**
  - New MCU?
  - Exceptional requirements (throughput, power, safety certification, etc.)
  - New product?
  - New customer?
  - Changing requirements?

- **Choose** model **based on risk**
  - Low risk: Can create detailed plan.
    - Big "up front" design
    - e.g. Waterfall
  - High risk: Use iterative / spiral method
    - Prototype high-risk parts first
    - e.g. Agile development

Waterfall (Idealized)

- Plan the work, and then work the plan
- BUFD: Big Up-Front Design
- Model implies that we and the customers know
  - All of the requirements up front
  - All of the interactions between components, etc.
  - How long it will take to write the software and debug it

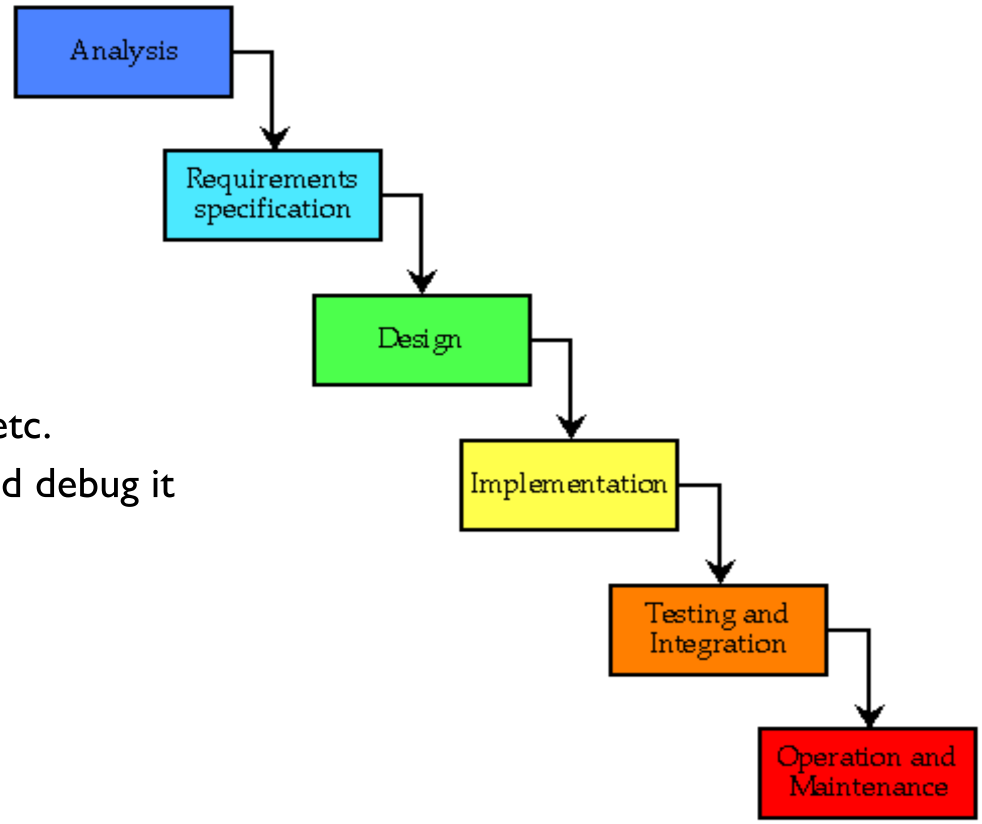


Diagram: Jon McCormack, Monash University

Waterfall (As Implemented)

- Reality: We are not omniscient, so there is plenty of backtracking

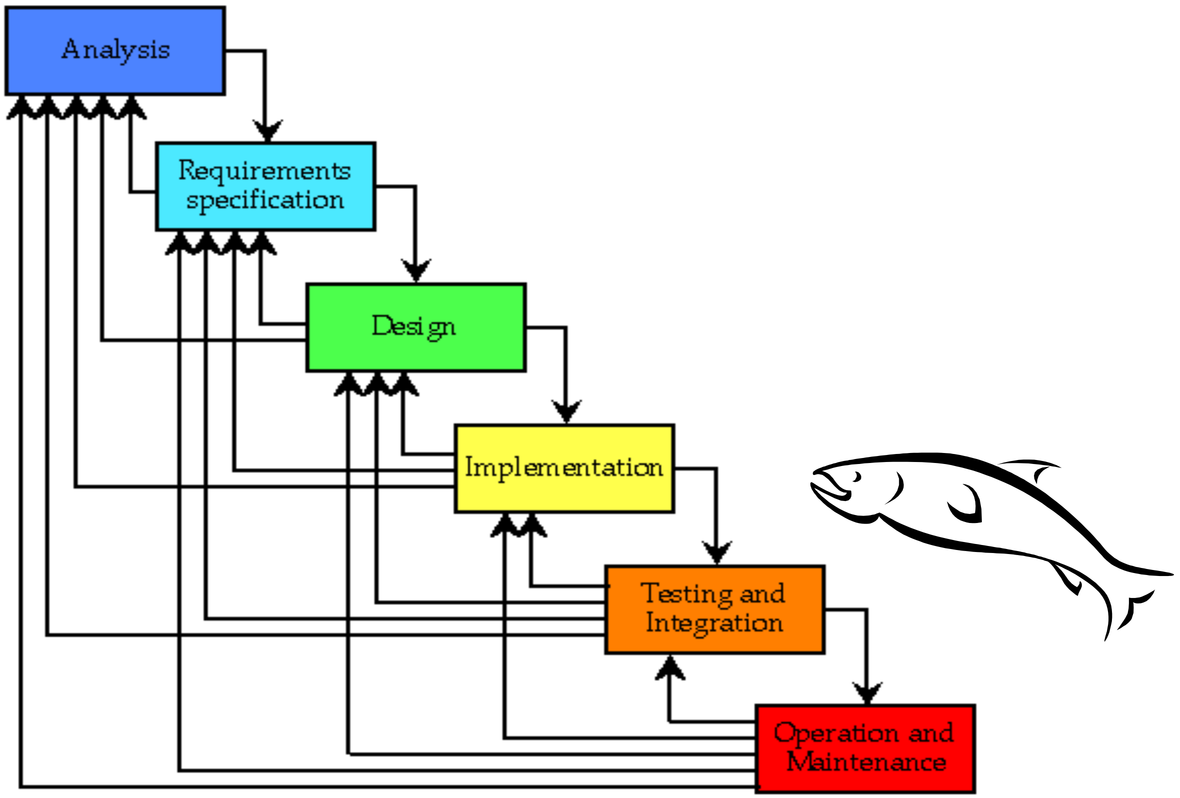


Diagram: Jon McCormack, Monash University

Agile Development: SCRUM

- http://www.mountaingoatsoftware.com/topics/scrum
- http://www.codeproject.com/KB/architecture/scrum.aspx

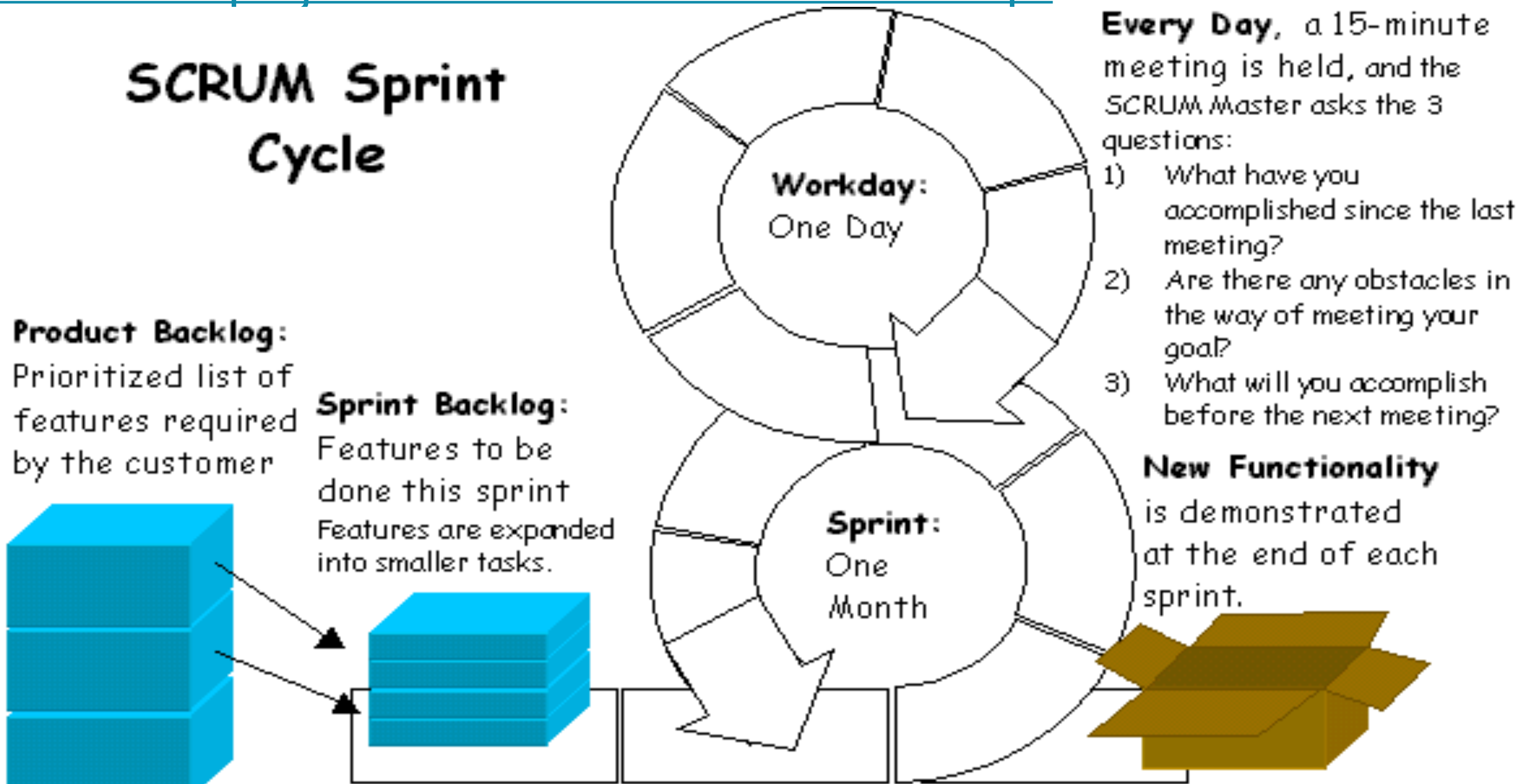


Diagram: Wikipedia

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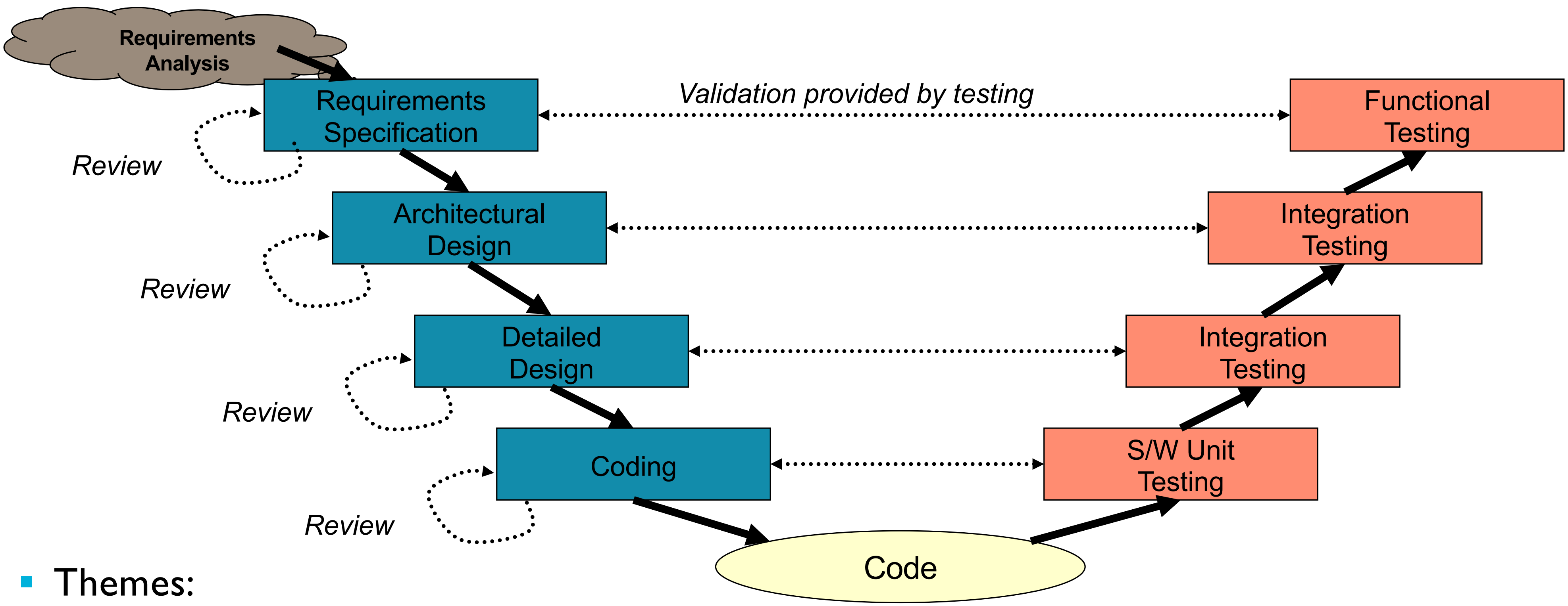
V Model Overview



- Themes:
  - Link front and back ends of life-cycle for efficiency
  - Provide "traceability" to ensure nothing falls through the cracks

1. Requirements Specification and Validation Plan

- Result of Requirements Analysis
- Should contain:
  - *Introduction* with goals and objectives of system
  - *Description of problem* to solve
  - *Functional description*
    - provides a "processing narrative" per function
    - lists and justifies design constraints
    - explains performance requirements
  - *Behavioral description* shows how system reacts to internal or external events and situations
    - State-based behavior
    - General control flow
    - General data flow
  - *Validation criteria*
    - tell us how we can decide that a system is acceptable. (*Are we done yet?*)
    - is the foundation for a validation test plan
  - *Bibliography and Appendix* refer to all documents related to project and provide supplementary information

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2. Architectural (High-Level) Design

- Architecture defines the structure of the system
  - Components
  - Externally visible properties of components
  - Relationships among components
- Architecture is a representation which lets the designer…
  - Analyze the design's effectiveness in meeting requirements
  - Consider alternative architectures early
  - Reduce down-stream implementation risks
- Architecture matters because…
  - It's small and simple enough to fit into a single person's brain (as opposed to comprehending the entire program's source code)
  - It gives stakeholders a way to describe and therefore discuss the system

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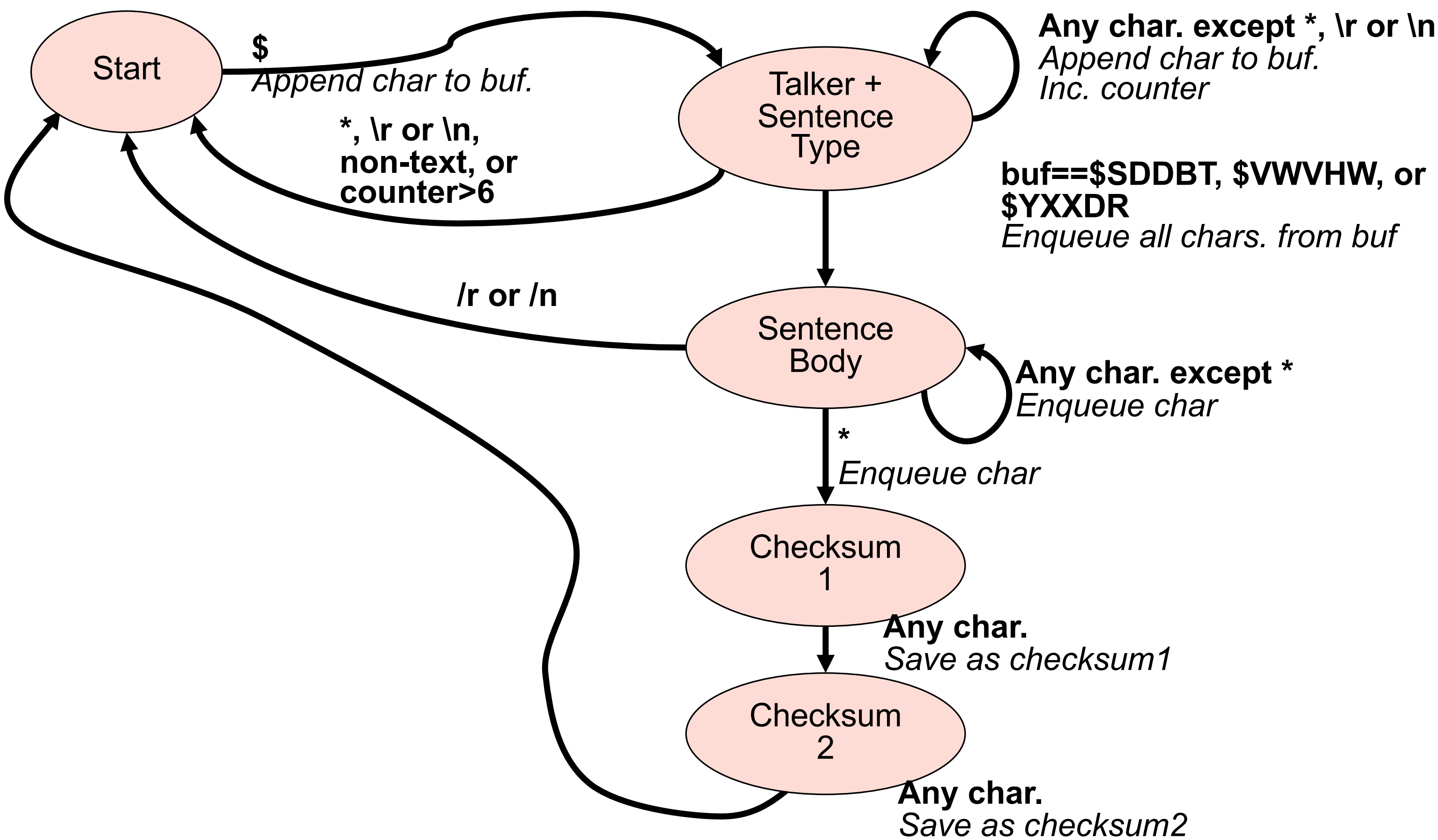
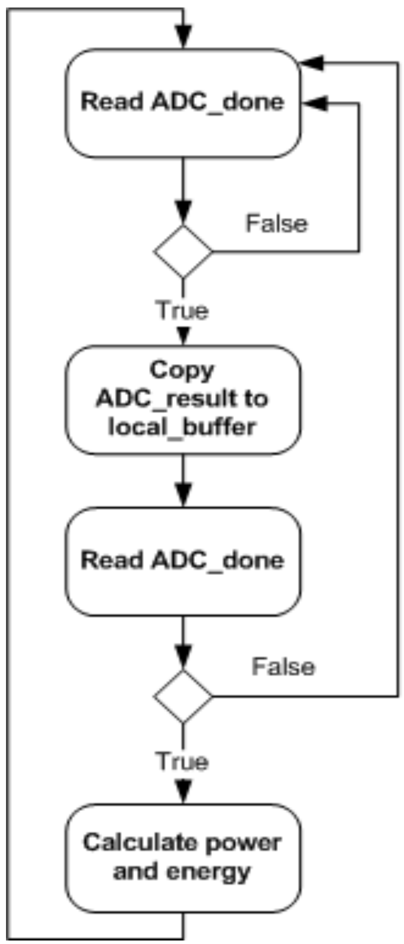
3. Detailed Design

- Describe aspects of how system behaves
  - Flow charts for control or data
  - State machine diagram
  - Event sequences
- Graphical representations very helpful
  - Can provide clear, single-page visualization of what system component should do

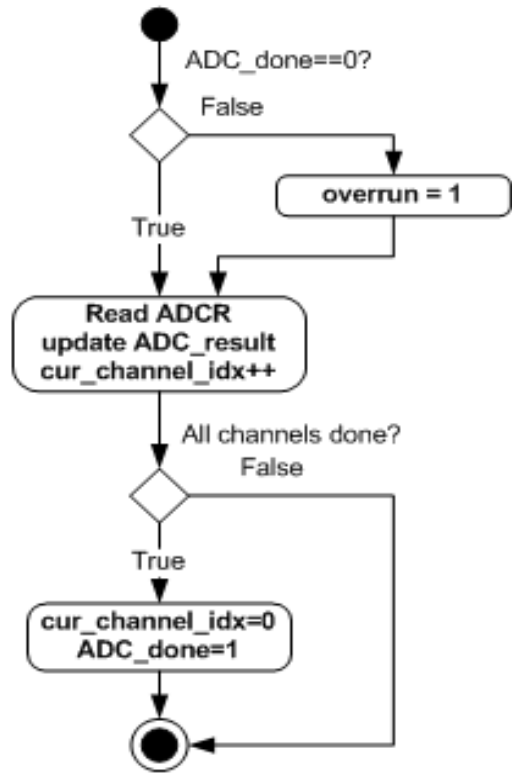
State Machine for Parsing NMEA-0183 (Serial Marine Comms)



Flowcharts

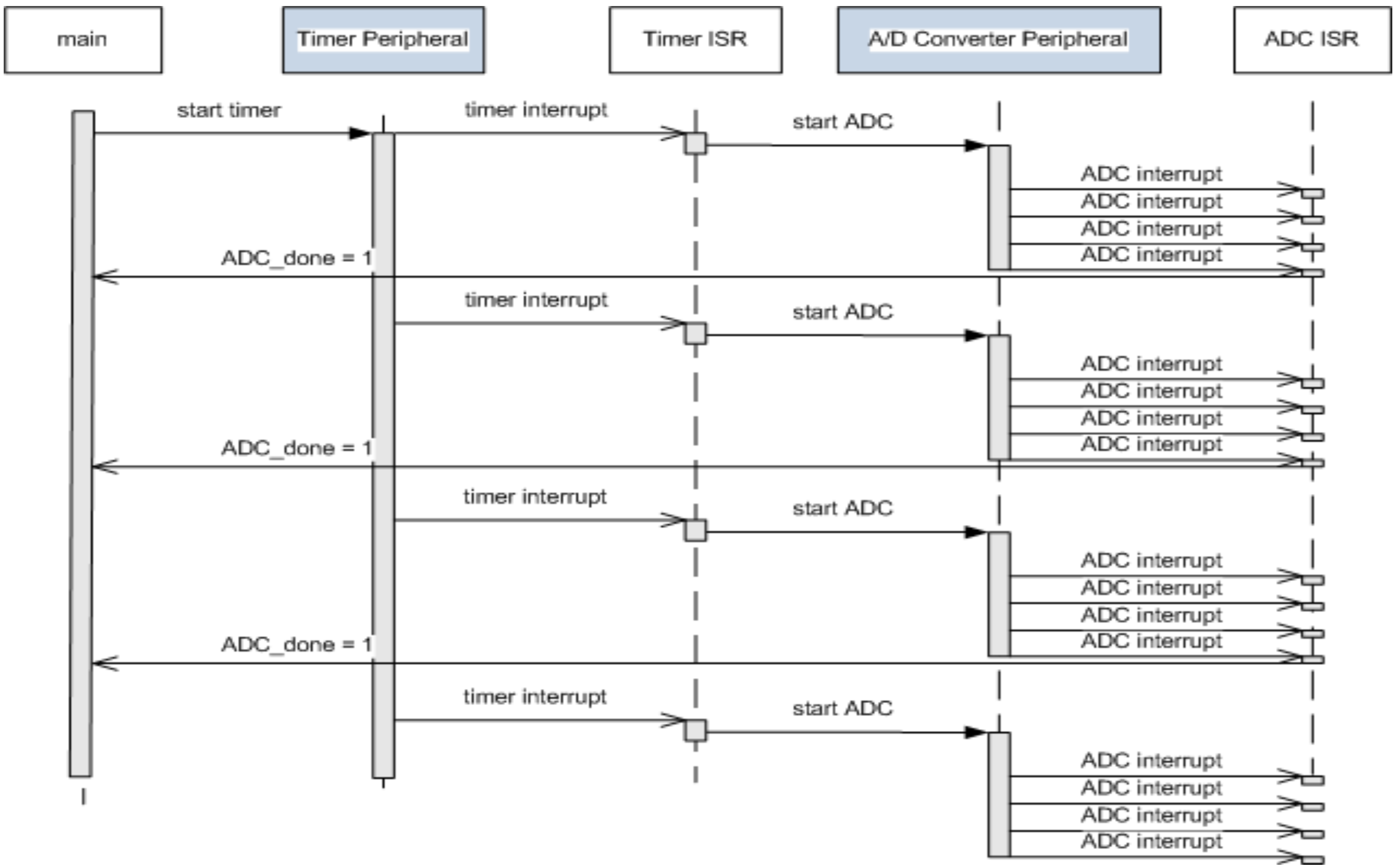


Read ADC_done
False
True
Copy
ADC_result to
local_buffer
Read ADC_done
False
True
Calculate power
and energy



ADC_done==0?
False
overrun = 1
True
Read ADCR
update ADC_result
cur_channel_idx++
All channels done?
False
True
cur_channel_idx=0
ADC_done=1

Sequence of Interactions between Components



4. Coding and Code Inspections

- Coding driven directly by Detailed Design Specification
- Use a version control system while developing the code
- Follow a coding standard
  - Eliminate stylistic variations which make understanding code more difficult
  - Avoid known questionable practices
  - Spell out best practices to make them easier to follow
- Perform code reviews
- Perform unit testing on modules as appropriate

Peer Code Review

- Inspect the code before testing it
- Extensive positive industry results from code inspections
  - IBM removed 82% of bugs
  - 9 hours saved by finding each defect
  - For AT&T quality rose by 1000% and productivity by 14%
- Finds bugs which testing often misses
  - 80% of the errors detected by HP's inspections were unlikely to be caught by testing
  - HP, Shell Research, Bell Northern, AT&T: inspections 20-30x more efficient than testing

5. Software Testing

- Testing IS NOT "the process of verifying the program works correctly"
  - The program probably won't work correctly in all possible cases
    - Professional programmers have 1-3 bugs per 100 lines of code after it is "done"
  - Testers shouldn't try to prove the program works correctly (impossible)
    - If you want and expect your program to work, you'll unconsciously miss failure because human beings are inherently biased
- The purpose of testing is to find problems quickly
  - Does the software violate the (performance) specifications?
  - Does the software violate unstated requirements?
- The purpose of finding problems is to fix the ones which matter
  - Fix the most important problems, as there isn't enough time to fix all of them
  - The *Pareto Principle* defines "the vital few, the trivial many"
    - Bugs are uneven in frequency – a vital few contribute the majority of the program failures. Fix these first.

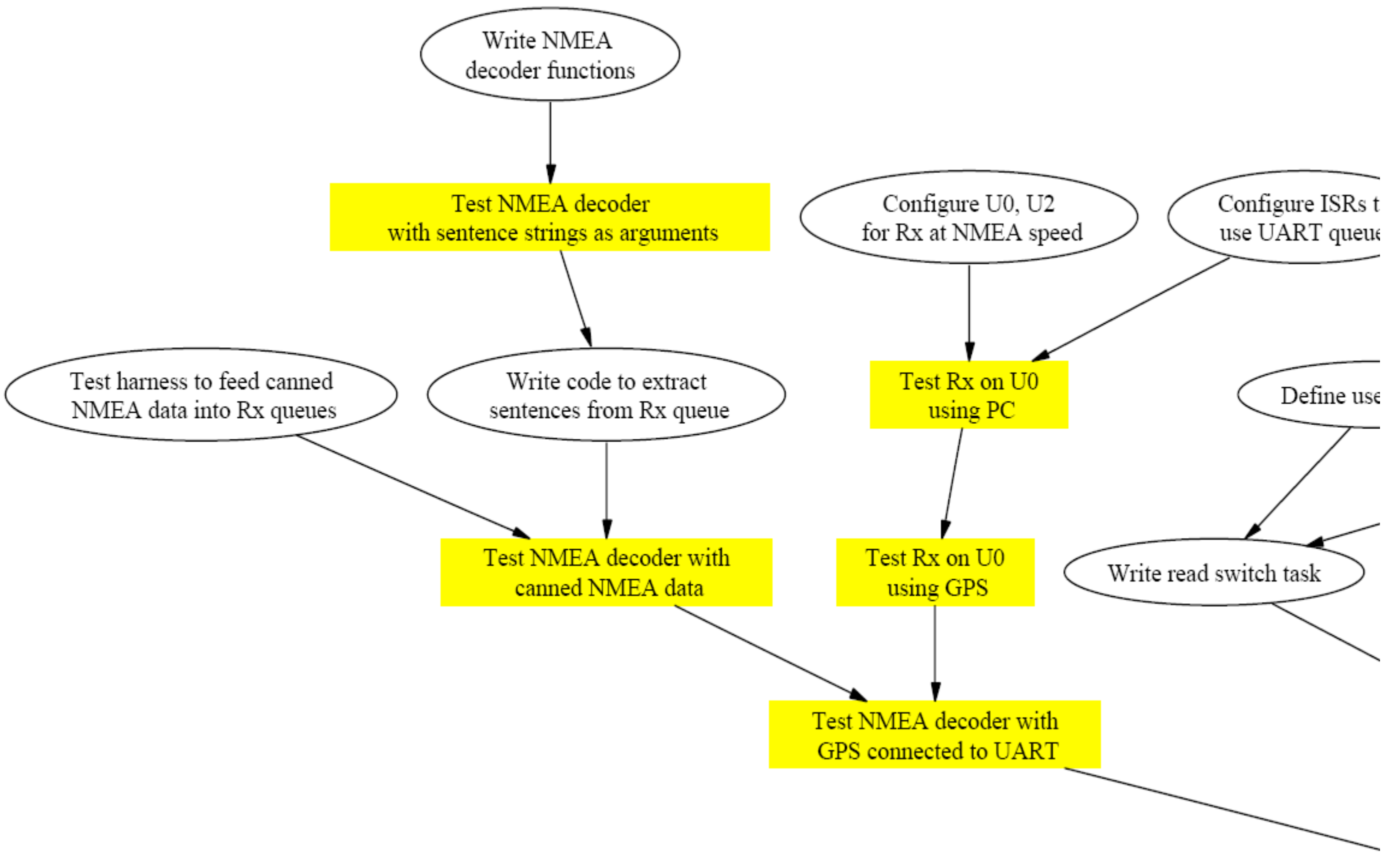
Approaches to Testing

- Incremental Testing
  - Code a function and then test it (*module/unit/element testing*)
  - Then test a few working functions together (*integration testing)*
    - Continue enlarging the scope of tests as you write new functions
  - Incremental testing requires extra code for the *test harness*
    - A *driver* function calls the function to be tested
    - A *stub* function might be needed to simulate a function called by the function under test, and which returns or modifies data.
    - The test harness can *automate* the testing of individual functions to detect later bugs
- Big Bang Testing
  - Code up all of the functions to create the system
  - Test the complete system
    - Plug and pray

Why Test Incrementally?

- Finding out what failed is much easier
  - With Big Bang, since no function has been thoroughly tested, most probably have bugs
  - Now the question is "Which bug in which module causes the failure I see?"
  - Errors in one module can make it difficult to test another module
    - Errors in fundamental modules (e.g. kernel) can appear as bugs in other many other dependent modules
- Less finger pointing = happier SW development team
  - It's clear who made the mistake, and it's clear who needs to fix it
- Better automation
  - Drivers and stubs initially require time to develop, but save time for future testing

Example Test Plan



6. Perform Project Retrospectives

- Goals – improve your engineering processes
  - Extract all useful information learned from the just-completed project – provide "virtual experience" to others
  - Provide positive non-confrontational feedback
  - Document problems and solutions clearly and concisely for future use

- Basic rule: problems need solutions

- Often small changes improve performance, but are easy to forget

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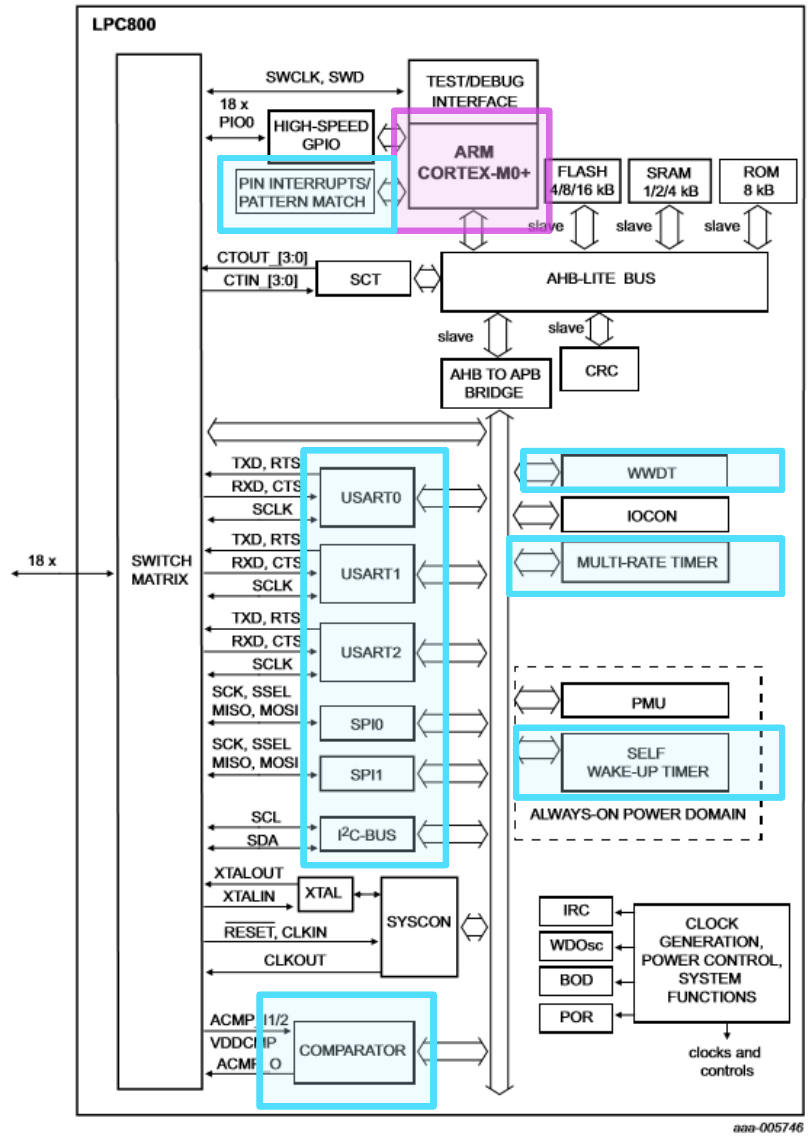
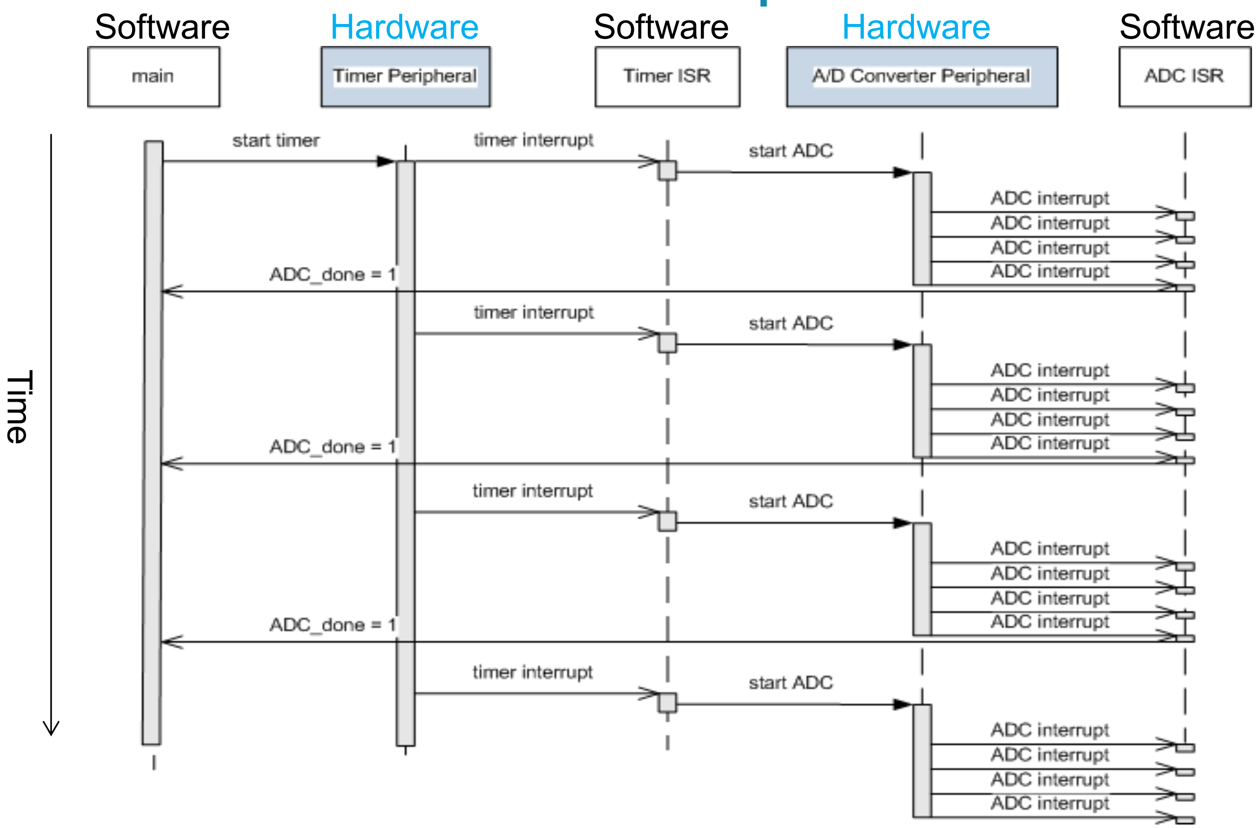
CONCURRENCY

MCU Hardware & Software for Concurrency

- CPU executes instructions from one or more threads of execution
- Specialized hardware peripherals add dedicated concurrent processing
  - ~~DMA - transferring data between memory and peripherals~~
  - Watchdog timer
  - Analog interfacing (comparator)
  - Timers
  - Communications with other devices
  - Detecting external signal events
- Peripherals use ***interrupts*** to notify CPU of events



Concurrent Hardware & Software Operation



- Embedded systems rely on both MCU ***hardware peripherals*** and ***software*** to get everything done on time

CPU Scheduling

- MCU's Interrupt system provides a basic scheduling approach for CPU
  - "Run this subroutine every time this hardware event occurs"
  - Is adequate for simple systems
- More complex systems need to support multiple concurrent independent threads of execution
  - Use task scheduler to share CPU
  - Different approaches to task scheduling
- How do we make the processor responsive? (How do we make it do the right things at the right times?)
  - If we have more software threads than hardware threads, we need to share the processor.

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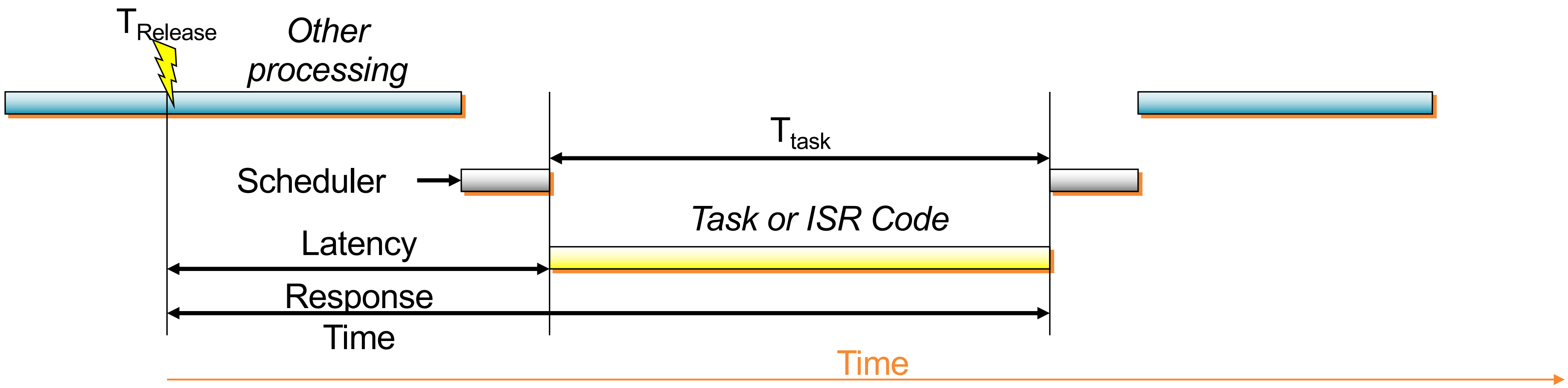
Definitions



- $T_{Release}(i)$ = Time at which task (or interrupt) i requests service/is released/is ready to run
- $T_{Latency}$ (i) = Delay between release and *start of service* for task i
- $T_{Response}(i)$ = Delay between request for service and *completion of service* for task i
- $T_{Task}(i)$ = Time needed to perform computations for task i
- $T_{ISR}(i)$ = Time needed to perform interrupt service routine i

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Scheduling Approaches

- Rely on MCU's hardware interrupt system to run right code
  - Event-triggered scheduling with interrupts
  - Works well for many simple systems
- Use software to schedule CPU's time
  - Static cyclic executive
  - Dynamic priority
    - Without task-level preemption
    - With task-level preemption

Event-Triggered Scheduling using Interrupts

- Basic architecture, useful for simple low-power devices
  - Very little code or time overhead
- Leverages built-in task dispatching of interrupt system
  - Can trigger ISRs with input changes, timer expiration, UART data reception, analog input level crossing comparator threshold
- Function types
  - Main function configures system and then goes to sleep
    - If interrupted, it goes right back to sleep
  - Only interrupts are used for normal program operation
- Example: bike computer
  - Int1: wheel rotation
  - Int2: mode key
  - Int3: clock
  - Output: Liquid Crystal Display

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Bike Computer Functions

Reset

```
Configure timer
inputs and
outputs

cur_time = 0;
rotations = 0;
tenth_miles = 0;

while (1) {
  sleep;
}
```

ISR 1: Wheel rotation

```
rotations++;
if (rotations>
  R_PER_MILE/10) {
  tenth_miles++;
  rotations = 0;
}
speed =
 circumference/
 (cur_time – prev_time);
compute avg_speed;
prev_time = cur_time;
return from interrupt
```

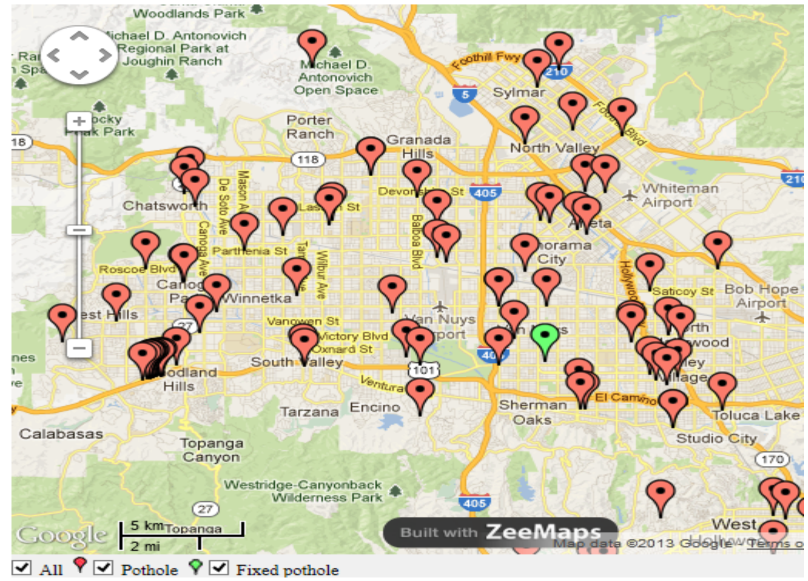
ISR 2: Mode Key

```
mode++;
mode = mode %
   NUM_MODES;
return from interrupt;
```

ISR 3: Time of Day Timer

```
cur_time ++;
lcd_refresh--;
if (lcd_refresh==0) {
 convert tenth_miles
    and display
 convert speed
    and display
  if (mode == 0)
    convert cur_time
      and display
  else
    convert avg_speed
      and display
  lcd_refresh =
     LCD_REF_PERIOD
}
```

A More Complex Application



- GPS-based Pothole Alarm and Moving Map
  - Sounds alarm when approaching a pothole
  - Display’s vehicle position on LCD
  - Also logs driver’s position information
  - Hardware: GPS, user switches, speaker, LCD, flash memory

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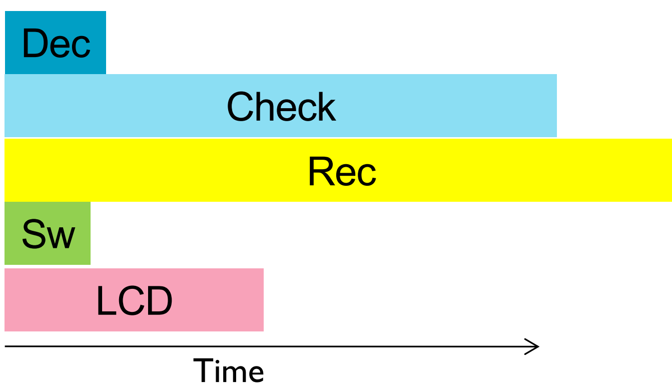
Application Software Tasks

- Dec: Decode GPS sentence to find current vehicle position.
- Check: Check to see if approaching any pothole locations. Takes longer as the number of potholes in database increases.
- Rec: Record position to flash memory. Takes a long time if erasing a block.
- Sw: Read user input switches. Run 10 times per second
- LCD: Update LCD with map. Run 4 times per second



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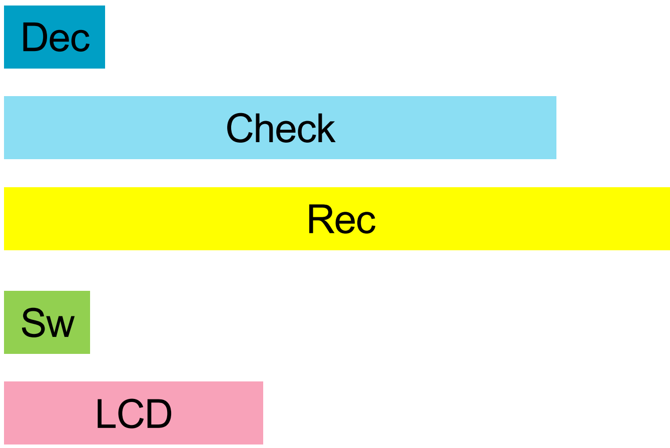
How do we schedule these tasks?



- Task scheduling: Deciding which task should be run now
- Two fundamental questions
  - **Do we run tasks in the same order every time?**
    - Yes: Static schedule (cyclic executive, round-robin)
    - No: Dynamic, prioritized schedule
  - **Can one task preempt another, or must it wait for completion?**
    - Yes: Preemptive
    - No: Non-preemptive (cooperative, run-to-completion)

Static Schedule (Cyclic Executive)

- Pros
  - Very simple
- Cons
  - Always run the same schedule, regardless of changing conditions and relative importance of tasks.
  - All tasks run at same rate. Changing rates requires adding extra calls to the function.
  - Maximum delay is sum of all task run times. Polling/execution rate is 1/maximum delay.

```
while (1){
        Dec();
        Check();
        Rec();
        Sw();
        LCD();
}
```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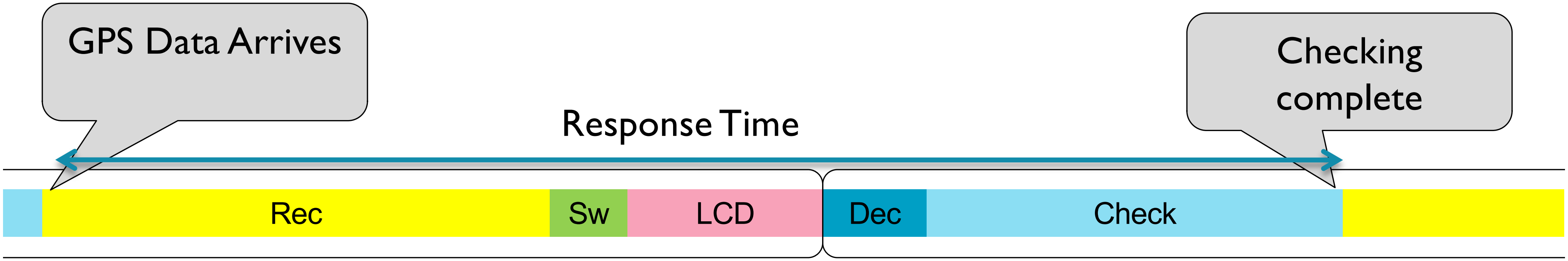
Static Schedule Example



- What if we receive GPS position right after Rec starts running?
- Delays
  - Have to wait for Rec, Sw, LCD before we start decoding position with Dec.
  - Have to wait for Rec, Sw, LCD, Dec, Check before we know if we are approaching a pothole!

Dynamic Scheduling

- Allow schedule to be computed on-the-fly
  - Based on importance or something else
  - Simplifies creating multi-rate systems
- Schedule based on importance
  - Prioritization means that less important tasks don't delay more important ones
- How often do we decide what to run?
  - Coarse grain – After a task finishes. Called *Run-to-Completion* (RTC) or non-preemptive
  - Fine grain – Any time. Called *Preemptive*, since one task can preempt another.

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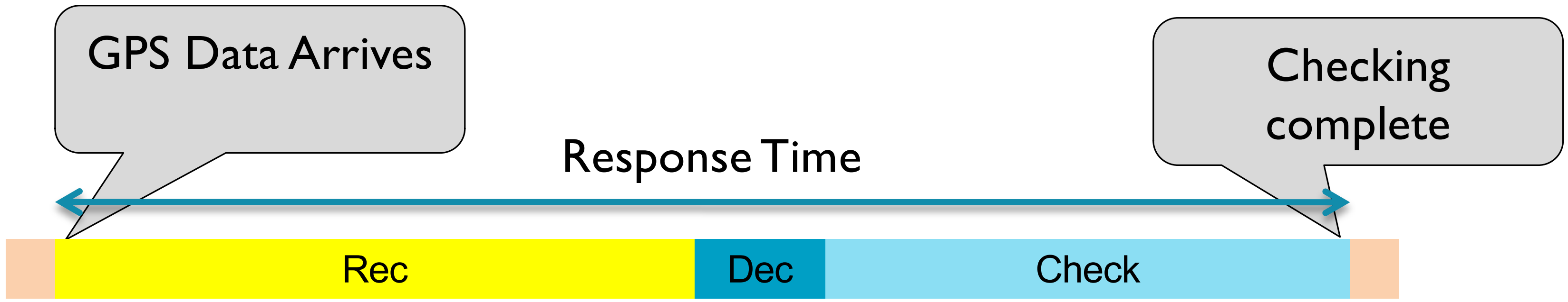
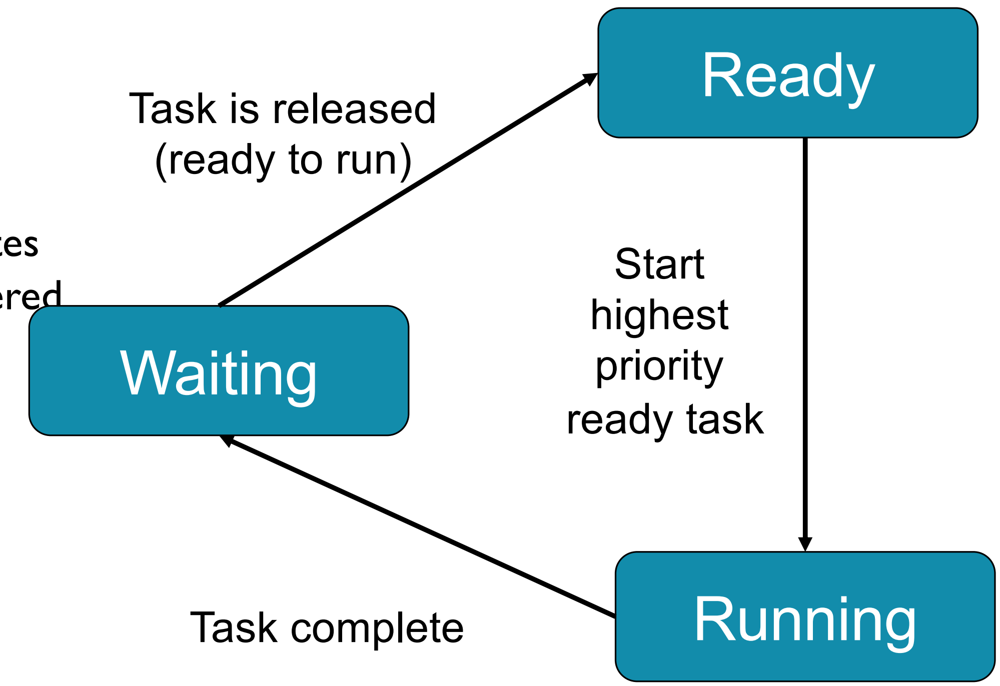
Dynamic Run to Completion (RTC) Schedule



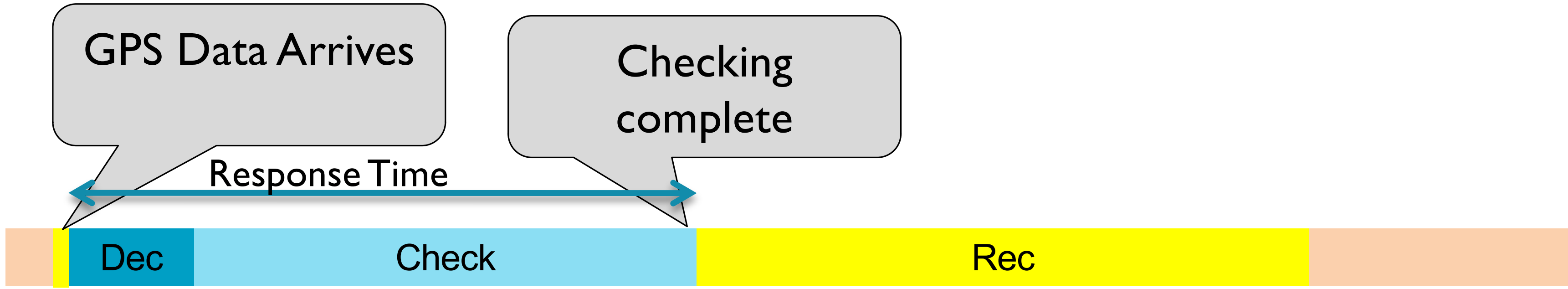
- RTC is "cooperative" / "non-preemptive"
- What if we receive GPS position right after Rec starts running?
- Delays
  - Have to wait for Rec to finish before we start decoding position with Dec.
  - Have to wait for Rec, Dec, Check before we know if we are approaching a pothole

RTC Task State and Scheduling Rules

- Run to Completion is *cooperative*.
- Scheduler chooses among *Ready* tasks for execution based on priority
- Scheduling Rules
  - If no task is running, scheduler starts the highest priority ready task
  - Once started, a task runs until it completes
  - Tasks then enter waiting state until triggered or released again

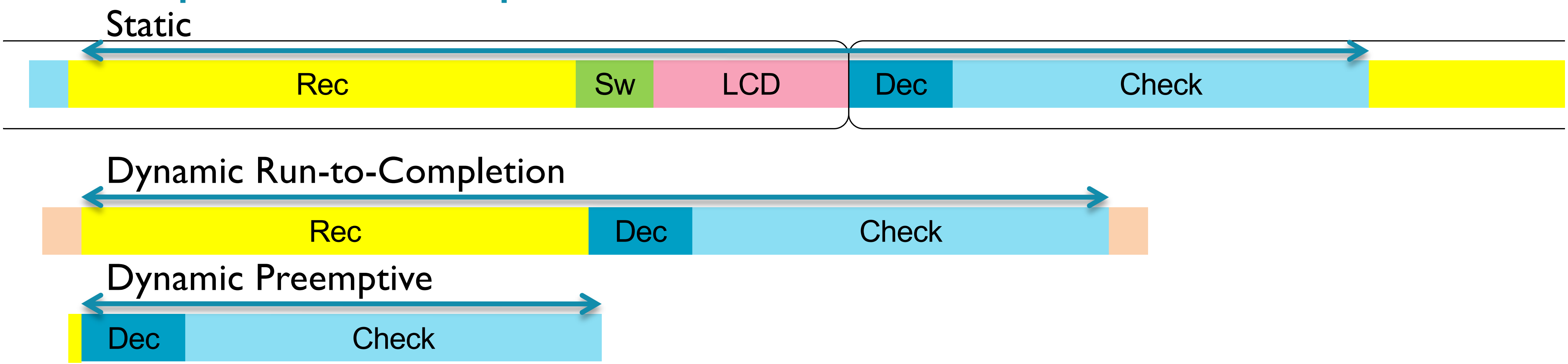


Dynamic Preemptive Schedule



- Preemption is "selfish" / *not cooperative*.
- What if we receive GPS position right after Rec starts running?
- Delays
  - Scheduler switches out Rec so we can start decoding position with Dec immediately
  - Have to wait for Dec, Check to complete before we know if we are approaching a pothole

Comparison of Response Times



- Pros
  - Preemption offers best response time
    - Can do more processing (support more potholes, or higher vehicle speed)
    - Or can lower processor speed, saving money, power

- Cons
  - Requires more complicated programming, more memory
  - Introduces vulnerability to data race conditions

Common Schedulers

- Cyclic executive - non-preemptive and static
- Run-to-completion - non-preemptive and dynamic
- Preemptive and dynamic

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Cyclic Executive with Interrupts

- Two priority levels
  - **main** code – background
  - Interrupts – foreground
- Example of a foreground / background system
- Interrupt routines run in foreground (high priority)
  - Run when triggered
  - Handle most urgent work
  - Set flags to request processing by main loop
- Main user code runs in background
  - Uses "round-robin" approach to pick tasks, takes turns
  - Tasks do not preempt each other

```
BOOL DeviceARequest, DeviceBRequest,
DeviceCRequest;
void interrupt HandleDeviceA(){
  /* do A's urgent work */
  ...
  DeviceARequest = TRUE;
}
void main(void) {
  while (TRUE) {
    if (DeviceARequest) {
      FinishDeviceA();
    }
    if (DeviceBRequest) {
      FinishDeviceB();
    }
    if (DeviceCRequest) {
      FinishDeviceC();
    }
  }
}
```


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Run-To-Completion Scheduler

- Use a ***scheduler*** function to run task functions at the right rates
  - Table stores information per task
    - Period: How many ticks between each task release
    - Release Time: how long until task is ready to run
    - ReadyToRun: task is ready to run immediately
  - Scheduler runs forever, examining schedule table which indicates tasks which are ready to run (have been "released")
  - A periodic timer interrupt triggers an ISR, which updates the schedule table
    - Decrements "time until next release"
    - If this time reaches 0, set the task's Run flag and reload its time with the period

- Follows a "run-to-completion" model
  - A task's execution is ***not interleaved*** with any other task
  - Only ISRs can interrupt a task
  - After ISR completes, the previously-running task resumes

- Priority is typically static, so can use a table with highest priority tasks first for a fast, simple scheduler implementation.

ARM

Preemptive Scheduler

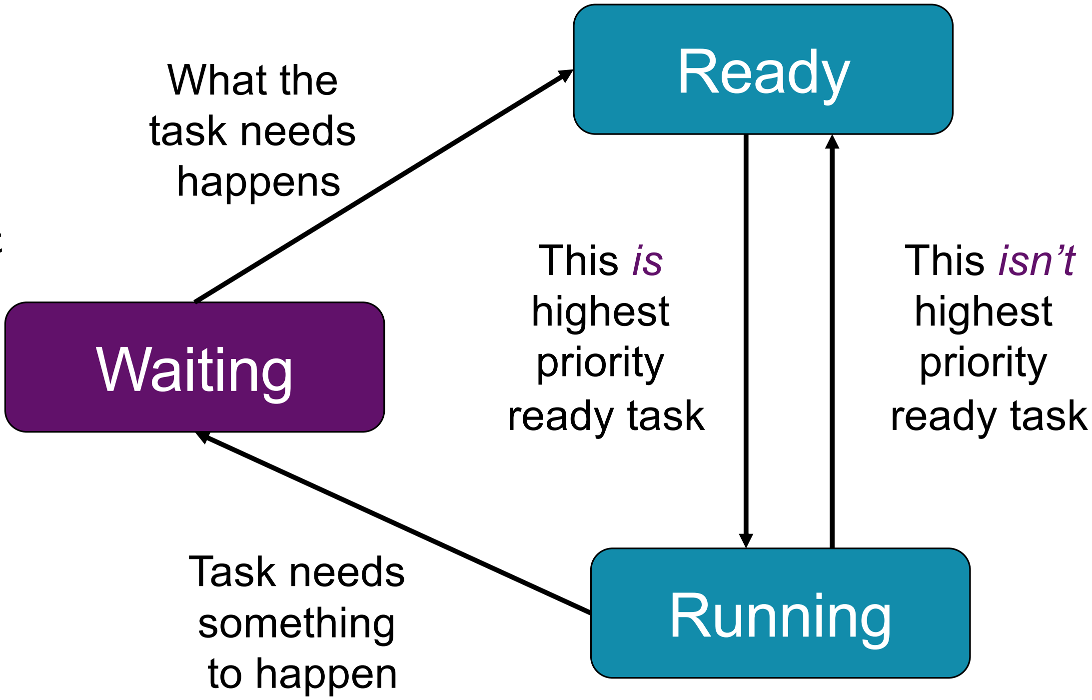
- Task functions need not run to completion, but can be interleaved with each other
  - Simplifies writing software
  - Improves response time
  - Introduces new potential problems

- Worst case response time for highest priority task does not depend on other tasks, only ISRs and scheduler
  - Lower priority tasks depend only on higher priority tasks

Task State and Scheduling Rules

- Scheduler chooses among *Ready* tasks for execution based on priority

- Scheduling Rules
  - A task's activities may lead it to *waiting (blocked)*
  - A *waiting* task never gets the CPU. It must be signaled by an ISR or another task.
  - Only the scheduler moves tasks between *ready* and *running*



What's an RTOS?

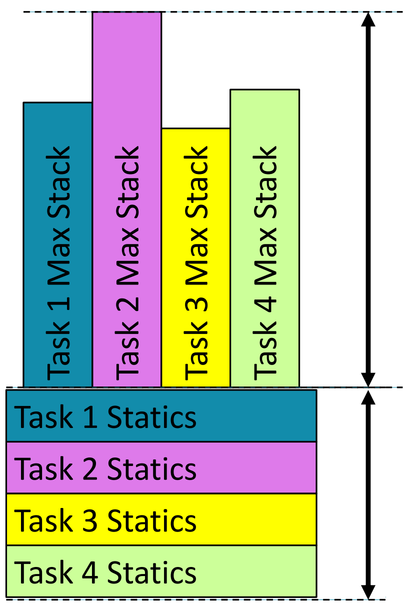
- What does Real-Time mean?
  - Can calculate and guarantee the *maximum response time* for each task and interrupt service routine
  - This "bounding" of response times allows use in hard-real-time systems (which have deadlines which must be met)
  - *Embedded systems RT is different than in other contexts.*

- What's in the RTOS
  - Task Scheduler
    - Preemptive, prioritized to minimize response times
    - Interrupt support
  - Core Integrated RTOS services
    - Inter-process communication and synchronization (safe data sharing)
    - Time management
  - Optional Integrated RTOS services
    - *I/O abstractions?*
    - *memory management?*
    - *file system?*
    - *networking support?*
    - *GUI??*

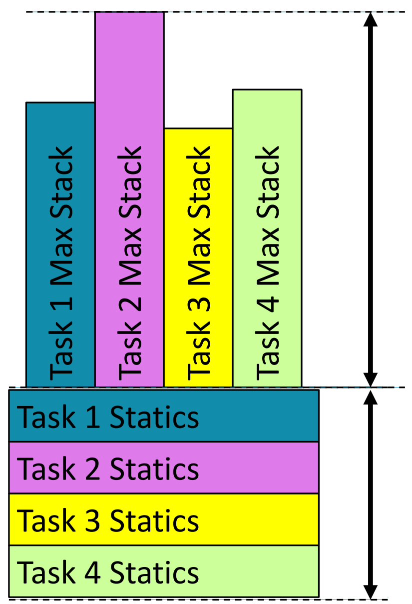
ARM

Comparison of RAM Requirements

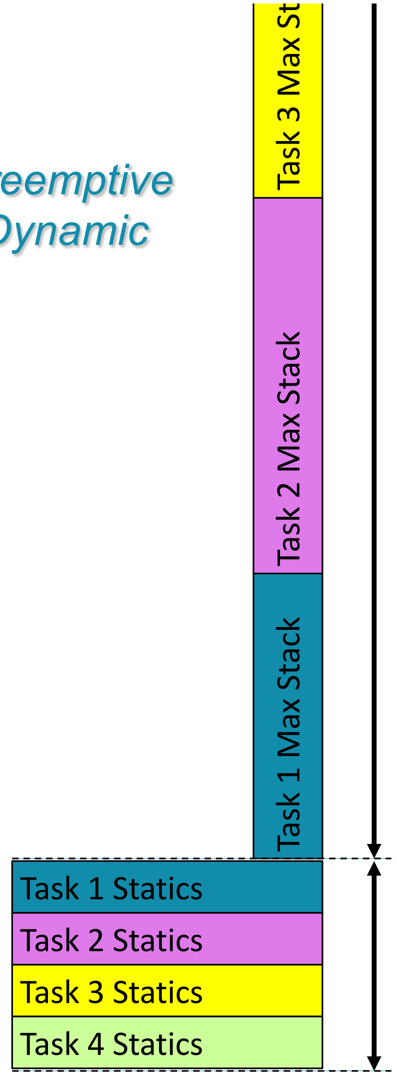
Non-preemptive Static



Non-preemptive Dynamic



Preemptive Dynamic



- Preemption requires space for each stack*
- Need space for all static variables (including globals)

**except for certain special cases*

End.

Material Source

ARM University
Worldwide Education Program

ARM-based Embedded Systems Design Lab-in-a-Box
Freescale Freedom Board Edition

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ARM