Multiple tasks and multiple processes.
- Scheduling
- Resource management
- Inter-process communication
- Performance

Preemptive real-time operating systems (RTOS)
- Book examples: freeRTOS.org, POSIX/Linux, Windows CE
- Keil/ARM: CMSIS Real-Time Operating System

Processes and UML.
Reactive systems

- Respond to external events.
  - Engine controller.
  - Seat belt monitor.
  - Process control.
  - Smart phone.

- Requires real-time response.
  - System architecture.
  - Program implementation.

- May require a chain reaction among multiple processors.
Tasks and processes

- A **task** is a functional description of a connected set of operations.
  
  *(Task can also mean a collection of processes.)*

- A **process** is a unique execution of a program.
  
  - Several copies of a program may run simultaneously or at different times.

- A process has its own state:
  
  - registers;
  
  - memory.

- The operating system manages processes.
Why multiple processes?

- Processes help us manage timing complexity:
  - time periods/rates differ between processes
    - depending on computational needs and deadlines
    - synchronous vs asynchronous execution
  - multiple & variable data/execution rates
    - multimedia (compressed vs uncompressed data)
    - automotive systems
  - asynchronous input
    - user interfaces - activated at random times (buttons, etc.)
    - communication systems
Example: engine control

- Tasks:
  - spark control
  - crankshaft sensing
  - fuel/air mixture
  - oxygen sensor
  - Kalman filter
  - state machine
  - gas pedal
## Typical rates in engine controllers

<table>
<thead>
<tr>
<th>Variable</th>
<th>Full range time (ms)</th>
<th>Update period (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine spark timing</td>
<td>300</td>
<td>2</td>
</tr>
<tr>
<td>Throttle</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Air flow</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Battery voltage</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td>Fuel flow</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>Recycled exhaust gas</td>
<td>500</td>
<td>25</td>
</tr>
<tr>
<td>Status switches</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Seconds</td>
<td>400</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>Seconds</td>
<td>1000</td>
</tr>
<tr>
<td>Spark (dwell)</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Fuel adjustment</td>
<td>80</td>
<td>8</td>
</tr>
<tr>
<td>Carburetor</td>
<td>500</td>
<td>25</td>
</tr>
<tr>
<td>Mode actuators</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Life without processes

- Code turns into a mess:
  - interruptions of one task for another
  - “spaghetti” code

```c
A_code();
...
B_code();
...
if (C) C_code();
...
A_code();
...
switch (x) {
  case C: C();
  case D: D();
  ...
```
Real-time systems

- Perform a computation to conform to external timing constraints.

  Deadline frequency:
  - Periodic.
  - Aperiodic.

  Deadline type:
  - Hard: failure to meet deadline causes system failure.
  - Soft: failure to meet deadline causes degraded response.
  - Firm: late response is useless but some late responses can be tolerated.

Process timing specifications:
- Release time: time at which process becomes ready.
- Deadline: time at which process must finish.
Release times and deadlines

- **Initiating event:** The process is initiated at the start of the period.
- **Period:** The process runs during a period.
- **Deadline:** The process must be completed by the deadline.

Diagram:
- **Time axis:** Extends from left to right.
- **Deadline box:** Located at the end of the period.
- **Process P1:** Runs within the period and completes at the deadline.
Rate requirements on processes

- **Period**: interval between process activations.
- **Rate**: reciprocal of period.
- Initiation rate may be higher than period---several copies of process run at once.
Timing violations

- What happens if a process doesn’t finish by its deadline?
  - **Hard deadline**: system fails if missed.
  - **Soft deadline**: user may notice, but system doesn’t necessarily fail.
Example: Space Shuttle software error

- Space Shuttle’s first launch was delayed by a software timing error:
  - Primary control system PASS and backup flight system BFS.
  - PASS used priority schedule (low priority could be skipped)
  - BFS used fixed time-slot schedule
  - BFS failed to synchronize with PASS.
  - A change to one routine added delay that threw off start time calculation.
  - 1 in 67 chance of timing problem.
Task graphs

- Tasks may have data dependencies---must execute in certain order.
- Task graph shows data/control dependencies between processes.
- **Task**: connected set of processes.
- **Task set**: One or more tasks.

![Task graph diagram](image-url)
Communication between tasks

- Task graph assumes that all processes in each task run at the same rate, tasks do not communicate.
- In reality, some amount of inter-task communication is necessary.
  - It's hard to require immediate response for multi-rate communication.
Process execution characteristics

- Process execution time $T_i$.
  - Execution time in absence of preemption.
  - Possible time units: seconds, clock cycles.
  - Worst-case, best-case execution time may be useful in some cases.

- Sources of variation:
  - Data dependencies.
  - Memory system.
  - CPU pipeline.
Utilization

- CPU utilization:
  - Fraction of the CPU that is doing useful work.
  - Often calculated assuming no scheduling overhead.

- Utilization:
  \[
  U = \frac{\text{CPU time for useful work}}{\text{total available CPU time}}
  = \frac{\sum_{t_1 \leq t \leq t_2} T(t)}{t_2 - t_1}
  = \frac{T}{t}
  \]
Scheduling feasibility

- Resource constraints make schedulability analysis NP-hard.
  - Must show that the deadlines are met for all timings of resource requests.
- Can we meet all deadlines?
  - Must be able to meet deadlines in all cases.
- How much CPU horsepower do we need to meet our deadlines?
Simple processor feasibility

Assume:

- No resource conflicts.
- Constant process execution times.

Require:

- \( T \geq \Sigma_i T_i \)
- Can’t use more than 100% of the CPU.
Hyperperiod

- **Hyperperiod**: least common multiple (LCM) of the task periods.
- Must look at the hyperperiod schedule to find all task interactions.
- Hyperperiod can be very long if task periods are not chosen carefully.
Hyperperiod example

- **Long hyperperiod:**
  - P1 7 ms.
  - P2 11 ms.
  - P3 15 ms.
  - LCM = 1155 ms.

- **Shorter hyperperiod:**
  - P1 8 ms.
  - P2 12 ms.
  - P3 16 ms.
  - LCM = 96 ms.
Simple processor feasibility example

- **P1** period 1 ms, CPU time 0.1 ms.
- **P2** period 1 ms, CPU time 0.2 ms.
- **P3** period 5 ms, CPU time 0.3 ms.

<table>
<thead>
<tr>
<th></th>
<th>period</th>
<th>CPU time</th>
<th>CPU time/LCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1 ms</td>
<td>0.1 ms</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>P2</td>
<td>1 ms</td>
<td>0.2 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>P3</td>
<td>5 ms</td>
<td>0.3 ms</td>
<td>0.3 ms</td>
</tr>
</tbody>
</table>

LCM = 5 ms

<table>
<thead>
<tr>
<th></th>
<th>total CPU/LCM</th>
<th>utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.8 ms</td>
<td>35%</td>
</tr>
</tbody>
</table>

Overheads for *Computers as Components 2nd ed.* © 2004 Wayne Wolf
TDMA: Time Division Multiple Access (access to CPU)
Schedule in time slots.
- Same process activation irrespective of workload.
- Time slots may be equal size or unequal. (usually equal)

\[ P = \text{HyperPeriod} \]
TDMA assumptions

- Schedule based on least common multiple (LCM) of the process periods.
- Trivial scheduler
  - very small “scheduling overhead”.

- Always gives same CPU utilization (assuming constant process execution times).
- Can’t handle unexpected loads.
  - Must schedule a time slot for aperiodic events.
    (Perhaps leave last time slot empty.)
TDMA schedulability example

- TDMA period = 10 ms.
- P1 CPU time 1 ms.
- P2 CPU time 3 ms.
- P3 CPU time 2 ms.
- P4 CPU time 2 ms.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
</tr>
<tr>
<td>P2</td>
</tr>
<tr>
<td>P3</td>
</tr>
<tr>
<td>P4</td>
</tr>
<tr>
<td>spare</td>
</tr>
<tr>
<td>utilization</td>
</tr>
</tbody>
</table>

* => Use half of time slot
Round-robin scheduling

- Schedule process only if ready.
  - Always test processes in the same order.
- Variations:
  - Constant system period.
  - Start round-robin again after finishing a round.

Empty slot (P1 wasn’t ready)
Round-robin assumptions

- Schedule based on least common multiple (LCM) of the process periods.
- Best done with equal time slots for processes.
- Simple scheduler
  - Low scheduling overhead.
  - Can be implemented in hardware.
- Can bound maximum CPU load.
  - May leave unused CPU cycles.
- Can be adapted to handle unexpected load.
  - Use time slots at end of period
Schedulability and overhead

- The scheduling process consumes CPU time.
  - Not all CPU time is available for processes.
  - Need code to control execution of processes.
  - Simplest implementation: process = subroutine.

- Scheduling overhead must be taken into account for exact schedule.
  - May be ignored if it is a small fraction of total execution time.
while loop implementation

- “Round Robin” schedule
- Simplest implementation has one loop.
  - No control over execution timing.

```c
while (TRUE) {
    p1();
    p2();
}
```
Timed loop implementation

- Encapsulate set of all processes in a single function that implements the task set.
  ```c
  void p_all()
  {
    p1();
    p2();
  }
  ```
- Use timer to control execution of task “p_all”.
  - Each process executed in each time interval
  - No control over timing of individual processes.
Multiple timers implementation

- Each task has its own function.
- Each task has its own timer.
  - May not have enough timers to implement all the rates.
- One timer interrupt may delay another

```c
void pA(){ /* rate A */
    p1();
    p3();
}

void pB(){ /* rate B */
    p2();
    p4();
    p5();
}
```
Timer + counter implementation

- Use a software count to divide the timer.
- Only works for clean multiples of the timer period.

```c
int p2count = 0;
void pall(){
    p1();
    if (p2count >= 2) {
        p2();
        p2count = 0;
    }
    else p2count++;
    p3();
}
```
Implementing processes

- All of these implementations are inadequate.
- Need better control over timing.
- Need a better mechanism than subroutines.
- Solve via Real-Time Operating System