CSCE 990: *Real-Time Systems*

Introduction

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Real-time System

- A **real-time system** is a system whose specification includes both logical and temporal correctness requirements.
  - » **Logical Correctness:** Produces correct outputs.
    - Can by checked, for example, by Hoare logic.
  - » **Temporal Correctness:** Produces outputs at the right time.
    - In this course, we spend much time on techniques for checking temporal correctness.
    - The question of how to specify temporal requirements, though enormously important, is shortchanged in this course.

Characteristics of Real-Time Systems

- Event-driven, reactive.
- High cost of failure.
- Concurrency/multiprogramming.
- Stand-alone/continuous operation.
- Reliability/fault-tolerance requirements.
- **Predictable behavior.**

Misconceptions about Real-Time Systems

(Stankovic '88)

- There is no science in real-time-system design.
  - We shall see…
- Advances in supercomputing hardware will take care of real-time requirements.
  - The old "buy a faster processor" argument…
- Real-time computing is equivalent to fast computing.
  - Only to ad agencies. To us, it means PREDICTABLE computing.

Misconceptions (Continued)

- Real-time programming is assembly coding, …
  - We would like to automate (as much as possible) real-time system design, instead of relying on clever hand-crafted code.
- "Real time" is performance engineering.
  - In real-time computing, timeliness is almost always more important than raw performance …
- "Real-time problems" have all been solved in other areas of CS or operations research.
  - OR people typically use stochastic queuing models or one-shot scheduling models to reason about systems.
  - CS people are usually interested in optimizing average-case performance.

Misconceptions (Continued)

- It is not meaningful to talk about guaranteeing real-time performance when things can fail.
  - Though things may fail, we certainly don't want the operating system to be the weakest link!
- Real-time systems function in a static environment.
  - Note true. We consider systems in which the operating mode may change dynamically.

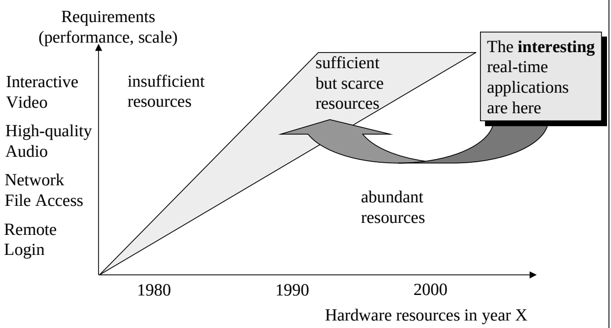
Are *All* Systems Real-Time Systems?

- **Question:** Is a payroll processing system a real-time system?
  - » It has a time constraint: Print the pay checks every two weeks.
- Perhaps it is a real-time system in a definitional sense, but it doesn't pay us to view it as such.
- We are interested in systems for which it is not *a priori* obvious how to meet timing constraints.

The "Window of Scarcity"

- Resources may be categorized as:
  - » **Abundant:** Virtually any system design methodology can be used to realize the timing requirements of the application.
  - » **Insufficient:** The application is ahead of the technology curve; no design methodology can be used to realize the timing requirements of the application.
  - » **Sufficient but scarce:** It is possible to realize the timing requirements of the application, but careful resource allocation is required.

Example: Interactive/Multimedia Applications

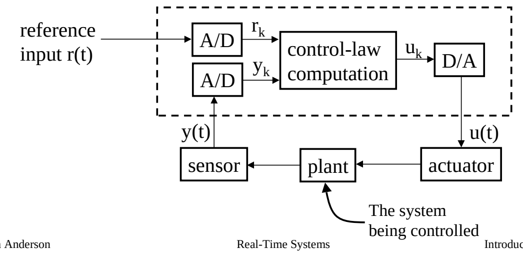


Example Real-Time Applications

(Chapter 1 of Liu)

Many real-time systems are **control systems**.

Example 1: A simple one-sensor, one-actuator control system.



Simple Control System (Continued)

Pseudo-code for this system:

```
set timer to interrupt periodically with period T;
at each timer interrupt do
      do analog-to-digital conversion to get y;
      compute control output u;
      output u and do digital-to-analog conversion;
od
```

T is called the **sampling period**. T is a key design choice. Typical range for T: seconds to milliseconds.

Multi-rate Control Systems

More complicated control systems have multiple sensors and actuators and must support control loops of different rates.

Example 2: Helicopter flight controller.

Do the following in each 1/180-sec. cycle:
- validate sensor data and select data source;
- if failure, reconfigure the system

Every sixth cycle do:
- keyboard input and mode selection;
- data normalization and coordinate transformation;
- tracking reference update
- control laws of the outer pitch-control loop;
- control laws of the outer roll-control loop;
- control laws of the outer yaw- and collective-control loop

Every other cycle do:
- control laws of the inner pitch-control loop;
- control laws of the inner roll- and collective-control loop

Compute the control laws of the inner yaw-control loop;

Output commands;

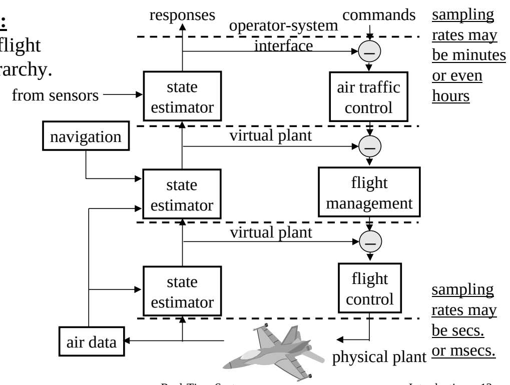
Carry out built-in test;

Wait until beginning of the next cycle

Note: Having only **harmonic** rates simplifies the system.

Hierarchical Control Systems

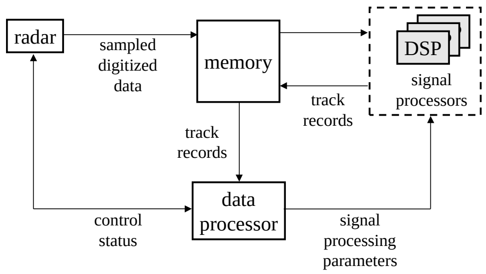
Example 3:
Air traffic-flight control hierarchy.



Signal-Processing Systems

- **Signal-processing systems** transform data from one form to another.
- **Examples:**
  - » Digital filtering.
  - » Video and voice compression/decompression.
  - » Radar signal processing.
- Response times range from a few milliseconds to a few seconds.

Example: Radar System



Other Real-Time Applications

- **Real-time databases.**
  - Transactions must complete by deadlines.
  - **Main dilemma:** Transaction scheduling algorithms and real-time scheduling algorithms often have conflicting goals.
  - Data may be subject to **absolute** and **relative temporal consistency** requirements.
- **Multimedia.**
  - Want to process audio and video frames at steady rates.
    - TV video rate is 30 frames/sec. HDTV is 60 frames/sec.
    - Telephone audio is 16 Kbits/sec. CD audio is 128 Kbits/sec.
  - **Other requirements:** Lip synchronization, low jitter, low end-to-end response times (if interactive).

Hard vs. Soft Real Time

(Chapter 2 of Liu)

» **Task:** A sequential piece of code.

» **Job:** Instance of a task.

» Jobs require **resources** to execute.

- **Example resources:** CPU, network, disk, critical section.
- We will simply call all hardware resources "processors".

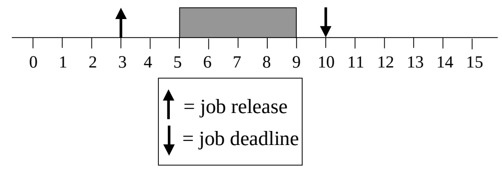
» **Release time of a job:** The time instant the job becomes ready to execute.

» **Deadline of a job:** The time instant by which the job must complete execution.

» **Relative deadline of a job:** "Deadline – Release time".

» **Response time of a job:** "Completion time – Release time".

Example



Job is released at time 3.
It's (absolute) deadline is at time 10.
It's relative deadline is 7.
It's response time is 6.

Hard Real-Time Systems

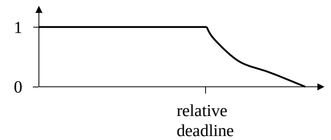
- A **hard deadline** *must* be met.
  - » If *any* hard deadline is *ever* missed, then the system is **incorrect**.
  - » Requires a means for **validating** that deadlines are met.
- **Hard real-time system:** A real-time system in which all deadlines are hard.
  - » We mostly consider hard real-time systems in this course.
- **Examples:** Nuclear power plant control, flight control.

Soft Real-Time Systems

- A **soft deadline** may *occasionally* be missed.
  - » **Question:** How to define "occasionally"?
- **Soft real-time system:** A real-time system in which some deadlines are soft.
- **Examples:** Telephone switches, multimedia applications.

Defining "Occasionally"

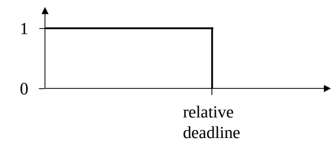
- **One Approach:** Use probabilistic requirements.
  - » For example, 99% of deadlines will be met.
- **Another Approach:** Define a "usefulness" function for each job:



- **Note:** Validation is trickier here.

Firm Deadlines

- **Firm deadline:** A soft deadline such that the corresponding job's usefulness function goes to 0 as soon as the deadline is reached (late jobs are of no use).



- Firm deadlines are not considered in Liu's book.

Reference Model

(Chapter 3 of Liu)

- Each job J_i is characterized by its release time r_i, absolute deadline d_i, relative deadline D_i, and execution time e_i.
- Sometimes a range of release times is specified: $[r_i^-, r_i^+]$. This range is called **release-time jitter**.
- Likewise, sometimes instead of e_i, execution time is specified to range over $[e_i^-, e_i^+]$.
  - » **Note:** It can be difficult to get a precise estimate of e_i (more on this later).

Periodic, Sporadic, Aperiodic Tasks

(Or, let the terminology wars begin…)

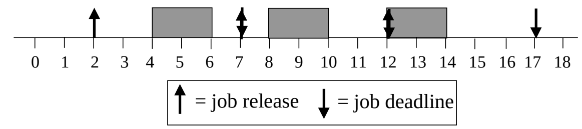
- **Periodic task:**
  - » We associate a **period p_i** with each task T_i.
  - » p_i is the minimum time between job releases.
- **Sporadic and aperiodic tasks:** Released at arbitrary times.
  - » **Sporadic:** Has a hard deadline.
  - » **Aperiodic:** Has no deadline or a soft deadline.

Warning!

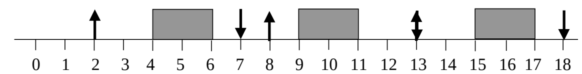
- What Liu calls “periodic”, the rest of the world calls “sporadic”.
- In the rest of the world, the period p_i of a periodic task T_i gives the **exact** spacing between job releases.

Examples

A periodic task T_i with $r_i = 2$, $p_i = 5$, $e_i = 2$, $D_i = 5$ executes like this according to the rest of the world:



According to Liu, it could execute like this:



To the rest of the world, this is a sporadic task.

Some Definitions for Periodic Task Sys.

- The jobs of task T_i are denoted $J_{i,1}$, $J_{i,2}$, … .
- $r_{i,1}$ (the release time of $J_{i,1}$) is called the **phase** of T_i.
  - » **Synchronous System:** Each task has a phase of 0.
  - » **Asynchronous System:** Phases are arbitrary.
- **Hyperperiod:** Least common multiple of $\{p_i\}$.
- **Task utilization:** $u_i = e_i/p_i$.
- **System utilization:** $U = \sum_{i=1..n} u_i$.

Task Dependencies

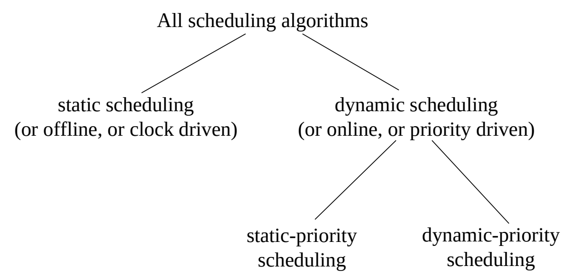
- Two main kinds of dependencies:
  - » Critical Sections.
  - » Precedence Constraints.
    - For example, job J_i may be constrained to be released only *after* job J_k completes.
- Tasks with no dependencies are called **independent**.
  - » In the first half of the course, we will consider only independent tasks.

Scheduling Algorithms

- We are generally interested in two kinds of algorithms:
  1. A **scheduler** or **scheduling algorithm**, which generates a schedule at runtime.
  2. A **feasibility analysis algorithm**, which checks if timing constraints are met.

- Usually (but not always) Algorithm 1 is pretty straightforward, while Algorithm 2 is more complex.

Classification of Scheduling Algorithms



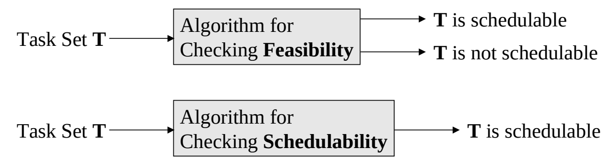
Optimality and Feasibility

- A schedule is **<u>feasible</u>** if all timing constraints are met.
  - The term "correct" is probably better — see the next slide.
- A task set T is **<u>schedulable</u>** using scheduling algorithm A if A always produces a feasible schedule for T.
- A scheduling algorithm is **<u>optimal</u>** if it always produces a feasible schedule when one exists (under any scheduling algorithm).
  - Can similarly define optimality for a class of schedulers, e.g., "an optimal static-priority scheduling algorithm."

Feasibility versus Schedulability

To most people in real-time community, the term **"feasibility"** is used to refer to an **<u>exact</u>** schedulability test, while the term **"schedulability"** is used to refer to a **<u>sufficient</u>** schedulability test.

You may find that these terms are used somewhat inconsistently in the papers we read.



Real-Time Research Repository

- For information on real-time research groups, conferences, journals, books, products, etc., have a look at:
  - » http://cs-www.bu.edu/pub/ieee-rts/Home.html