University of Glasgow | School of Computing Science

Advanced Operating Systems (M)

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Rationale

- Radical changes to computing landscape;
  - Desktop PC becoming irrelevant
  - Heterogeneous, multicore, mobile, and real-time systems – smart phones, tablets – now ubiquitous
- Not reflected by corresponding change in operating system design practice
- This course will...
  - review research on systems programming techniques and operating systems design;
  - discuss the limitations of deployed systems; and
  - show how the operating system infrastructure might evolve to address the challenges of supporting modern computing systems.

Aims and Objectives

- To explore programming language and operating system facilities essential to implement real-time, reactive, and embedded systems
- To discuss limitations of widely-used operating systems, introduce new design approaches to address challenges of security, robustness, and concurrency
- To give an understanding of practical engineering issues in real-time and concurrent systems; and suggest appropriate implementation techniques

Intended Learning Outcomes (1)

- At the end of this course, you should be able to:
  - clearly differentiate the issues that arise in designing real-time systems; analyse a variety of real-time scheduling techniques, prove correctness of the resulting schedule; implement basic scheduling algorithms;
  - understand how to apply real-time scheduling theory to the design and implementation of a real-world system using the POSIX real-time extensions, and be able to demonstrate how to manage resource access in such a system;
  - describe how embedded systems are constructed, and discuss the limitations and advantages of C as a systems programming language; understand how managed code and advanced type systems might be used in the design and implementation of future operating systems;
  - discuss the advantages and disadvantages of integrating garbage collection with the operating system/runtime; understand the operation of popular garbage collection algorithms; know when it might be appropriate to apply garbage collection and managed runtimes to real-time systems;
  - …

Intended Learning Outcomes (2)

…

- understand the impact of heterogeneous multicore systems on operating systems; compare and evaluate different programming models for concurrent systems, their implementation, and their impact on operating systems;
- construct and/or analyse simple concurrent programs using transactional memory and/or message passing, to understand the trade-offs and implementation decisions.

Course Outline

- Real-time operating systems
  - Real-time scheduling
  - Resource allocation
  - Programming model
- Garbage collection
- Implications of multicore systems
  - Message passing
  - Transactions
  - General purpose GPU programming models

Timetable (1)

Week	Lecture	Subject
1	Lecture 1	Principles of Real-time Systems
	Lecture 2	Real-time Scheduling of Periodic Tasks (1)
	Lecture 3	Real-time Scheduling of Periodic Tasks (2)
2		No lectures
	Tutorial 1	Real-time Scheduling of Periodic Tasks
3		No lectures
4	Lecture 4	Real-time Scheduling of Aperiodic and Sporadic Tasks (1)
	Lecture 5	Real-time Scheduling of Aperiodic and Sporadic Tasks (2)
	Tutorial 2	Real-time Scheduling of Aperiodic and Sporadic Tasks
5	Lecture 6	Resource Management
	Lecture 7	Real-time & Embedded Systems Programming
	Tutorial 3	Resource Management/Systems Programming

Timetable (2)

Week	Lecture	Subject
6	Lecture 8	Garbage Collection (1)
	Lecture 9	Garbage Collection (2)
	Tutorial 4	Garbage Collection
7	Lecture 10	Implications of Multicore Systems
	Lecture 11	Message Passing (1)
	Lecture 12	Message Passing (2)
8	Tutorial 5	Message Passing
	Lecture 13	Transactions
	Tutorial 6	Transactions
9		No lectures
10	Lecture 14	General Purpose GPU Programming (1)
	Lecture 15	General Purpose GPU Programming (2)
	Tutorial 7	General Purpose GPU Programming

Assessment

- Level M course; 10 credits
- Coursework (20%)

Exercise	Weight	Topic	Set	Due
1	4%	Scheduling periodic tasks	Tutorial 1	Tutorial 2
2	4%	Scheduling aperiodic/sporadic tasks	Tutorial 2	Tutorial 3
3	12%	Programming message passing systems	Tutorial 5	Tutorial 7

- Examination (80%)
  - Two hours duration; sample and past papers are available on Moodle
  - All material in the lectures, tutorials, and cited papers is examinable
  - Aim is to test your understanding of the material, not to test your memory of all the details; explain why – don't just recite what

Pre- and co-requisites

- Required pre-requisites:
  - Computer Systems 2
  - Operating Systems 3
  - Advanced Programming 3
  - Functional Programming 4
- Recommended co-requisites:
  - Computer Architecture 4

Required Reading

- No single set text book
- Research papers will be cited
  - DOIs will be provided; resolve via http://dx.doi.org/ – some papers behind paywalls, but accessible for free from on campus
  - You are expected to read and understand papers; it will be beneficial to follow-up on some of the references and do further background reading
    - Critical reading of a research paper is difficult and requires practice; read in a structured manner, not end-to-end, thinking about the material as you go
    - Advice on paper reading: http://www.eecs.harvard.edu/~michaelm/postscripts/ReadPaper.pdf
    - S. Keshav, “How to Read a Paper”, ACM Computer Communication Review, 37(3), July 2007 DOI: 10.1145/1273445.1273458
- Tutorials allow for discussion of papers and lectured material

Resources and Contact Details

- Lecture slides and other materials are on Moodle
  - Also http://csperkins.org/teaching/adv-os/
  - Printed lecture handouts will not be provided – learning is enhanced by taking your own notes during lectures and tutorials

- Course coordinator:
  - Dr Colin Perkins, Room S101b, Lilybank Gardens
  - Email: colin.perkins@glasgow.ac.uk
  - No assigned office hours – email to make appointment if needed

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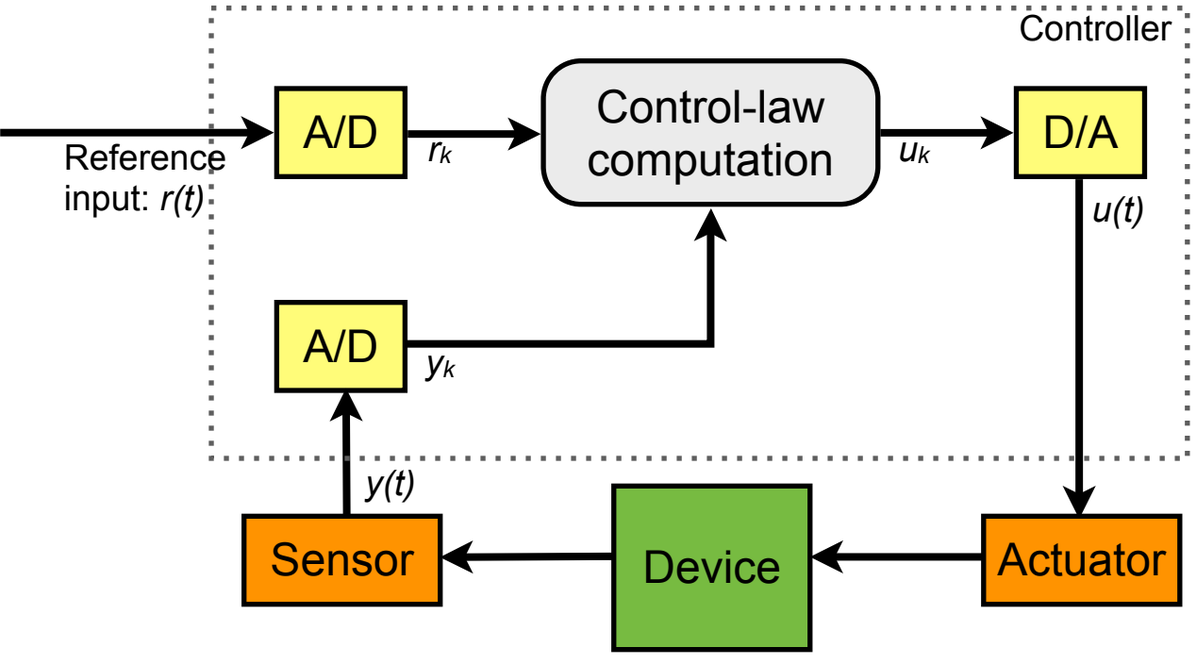
Principles of Real-time Systems

Advanced Operating Systems
Lecture 1

Introduction to Real-time Systems

- Real-time systems deliver services while meeting timing constraints
  - Not necessarily fast, but must meet some deadline
  - Many real-time systems embedded as part of a larger device or system: washing machine, photocopier, phone, car, aircraft, industrial plant, etc.
- Frequently require validation for correctness
  - Many embedded real-time systems are safety critical – if they don't work in a timely and correct basis, serious consequences result
  - Bugs in embedded real-time systems can be difficult or expensive to repair – e.g., can't easily update software in a car!

Typical System Model



- Control a device using actuator, based on sampled sensor data
  - Control loop compares measured value and reference
  - Depends on correct control law computation, reference input, accuracy of measurements
  - Time between measurements of $y(t)$, $r(t)$ is the sampling period, T
  - Small T better approximates analogue control but large T needs less processor time; if T is too large, oscillation will result as the system fails to keep up with changes in the input

- Simple control loop conceptually easy to implement
- Complexity comes from multiple control loops running at different rates, of if the system contains aperiodic components

Implementation Considerations

- Some real-time embedded systems are complex, implemented on high-performance hardware
  - E.g., industrial plant control, avionics and flight control systems
- But, many implemented on hardware that is low cost, low power, and low performance, but light-weight and robust
  - E.g., consumer goods
  - Often implemented in C or assembler, fitting within a few kilobytes of memory; correctness primary concern, efficiency a close second
- Desire proofs of correctness, ways of raising the level of abstraction programming such systems

Reference Model for Real-time Systems

- A reference model and consistent terminology let us reason about real-time systems
  - Cannot prove correctness without well-defined system model
- Reference model needs to characterise:
  - Applications running on a system (*jobs* and *tasks*) and the *processors* supporting their execution
  - The *resources* those applications use
  - Scheduling algorithms to determine when applications execute and use resources, and the *timing constraints* they must meet

Jobs, Tasks, Processors, and Resources

- A *job* is a unit of work scheduled and executed by the system
- A *task* $T = \{J_1, J_2, \ldots, J_n\}$ is a set of related jobs that together perform some operation

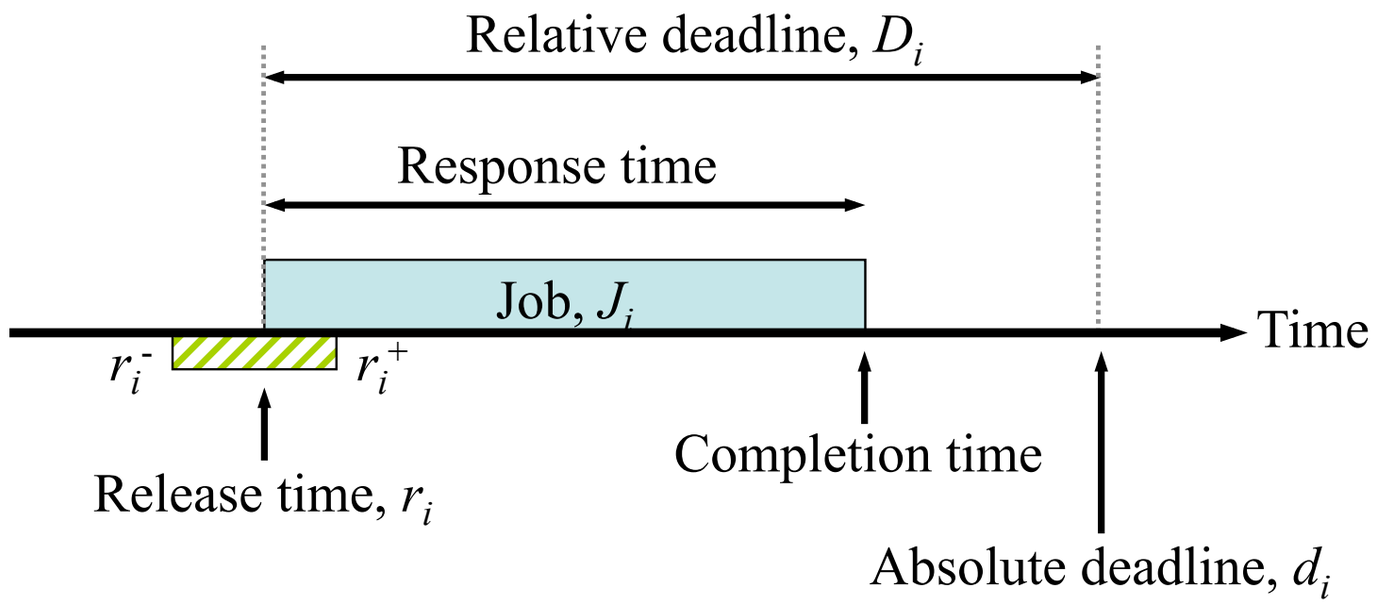
- Jobs execute on a *processor* and may depend on some *resources*
- A *scheduling algorithm* describes how jobs execute

- Processors are active devices on which jobs are scheduled
  - E.g., threads scheduled on a CPU, data scheduled on a transmission link
  - A processor has a speed attribute, that determines the rate of progress of jobs executing on that processor

- A resource, R, is a passive entity on which jobs may depend
  - A hardware device, for example
- Resources have different types or sizes, but have no speed attribute and are not consumed by use
- Jobs compete for resources, and can block if a resource is in use

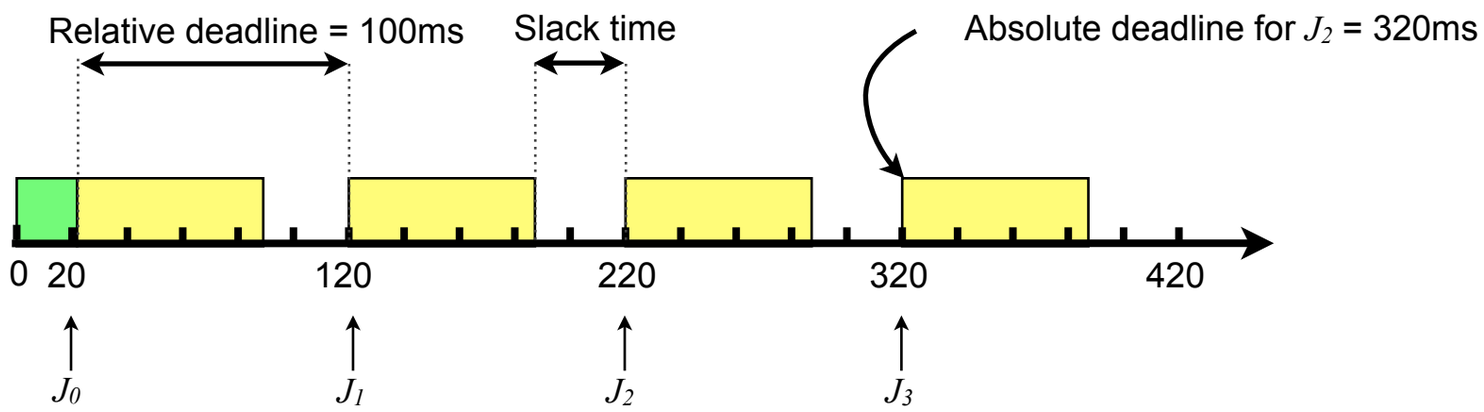
Timing Constraints

- Job J_i executes for time e_i – time to finish J_i given sole use of processor, and all required resources
  - Execution time depends on input data – use worst case for safety
- Jobs have timing constraints – relative or absolute deadlines:



Timing Constraints: Example

- A system to monitor and control a heating furnace
  - The system takes 20ms to initialise when turned on
  - After initialisation, every 100ms, the system:
    - Samples and reads the temperature sensor
    - Computes the control-law for the furnace to process the temperature readings, determine the correct flow rates of fuel, air, and coolant
    - Adjusts the flow rates to match the computed values
- The system can be modelled as a task, T, comprising jobs $J_0, J_1, \ldots, J_k, \ldots$
  - The release time of J_k is $20 + (k \times 100)$ms
  - The relative deadline of J_k is 100ms; the absolute deadline is $20 + ((k + 1) \times 100)$ms



Periodic Tasks

- If jobs occur on a regular cycle, the task is *periodic* and characterised by parameters $T_i = (\varphi_i, p_i, e_i, D_i)$
  - Phase, φ_i, of the task is the release time of the first job (if omitted, $\varphi_i = 0$)
  - Period, p_i, of the task is the time between release of consecutive jobs
  - Execution time, e_i, of the task is the maximum execution time of the jobs
  - Relative deadline, D_i, is the minimum relative deadline of the jobs (if omitted, $D_i = p_i$)
  - Utilisation of a task is $u_i = e_i / p_i$ and measures the fraction of time for which the task executes
  - The total utilisation of a system $U = \sum_i u_i$
- Common in real-world control systems

Aperiodic and Sporadic Tasks

- If jobs have unpredictable release times, a task is termed *aperiodic*
- A *sporadic* task is an aperiodic task where the jobs have deadlines once released

- Greatly complicate reasoning about correctness
  - Helpful if bounds or probability distributions of release times and deadlines can be determined

The Real-time Scheduling Problem

- Need to schedule jobs and manage resources
- In a *valid* schedule for a set of jobs:
  - Processors are assigned at most one job at once; jobs are assigned at most one processor at once
  - No job is scheduled before its release
  - Processor time assigned to each job equals its maximum execution time
  - All the precedence and resource usage constraints are satisfied
- A *feasible* schedule is valid, and jobs meet timing constraints – not all valid schedules are feasible
- An *optimal* scheduling algorithm will always find a feasible schedule if it exists

Hard and Soft Real-time Systems

- The firmness of timing constraints affects how we engineer the system
  - If a job must never miss its deadline, the system is *hard real-time*
    - A timing constraint is hard is failure to meet it is considered a fatal error
    - A timing constraint is hard if the usefulness of the results falls off abruptly at the deadline
    - A timing constraint is hard if the user requires validation (formal proof or exhaustive simulation, potentially with legal penalties) that the system always meets the constraint
  - If some deadlines can be missed occasionally, with low probability, then the system is described as *soft real-time*
- Hard and soft real-time are two ends of a spectrum
  - In many practical systems, the constraints are probabilistic, and depend on the likelihood and consequences of failure
  - No system is guaranteed to *always* meet its deadlines: there is always some probability of failure

Further Reading

- Next few lectures will focus on real-time scheduling

- Recommended reading:
  Jane W. S. Liu, “Real-Time Systems”, Prentice Hall, 2000, ISBN 0130996513

