Real-Time Systems

Stefan M. Petters

Australian Government
Department of Communications, Information Technology and the Arts
Australian Research Council
NICTA Members
NICTA Partners

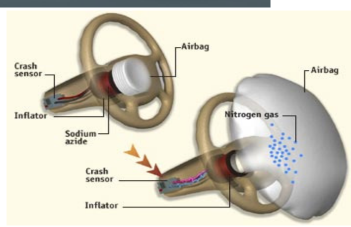
Lecture Content

- Definition of Real-Time Systems (RTS)
- Scheduling in RTS
- Schedulability Analysis
- Worst Case Execution Time Analysis
- Time and Distributed RTS
- Rate Based Scheduling

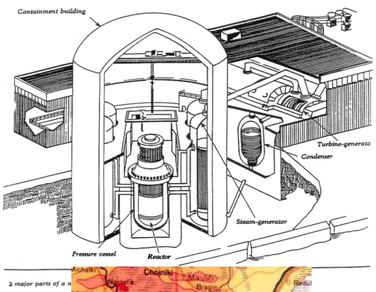
Definition

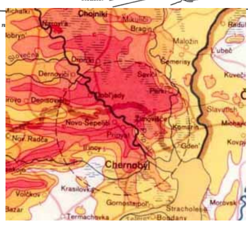
- A real-time system is any information processing system which has to respond to externally generated input stimuli within a finite and specified period
  - the correctness depends not only on the logical result but also the time it was delivered
  - failure to respond is as bad as the wrong response!

Real-Time Systems

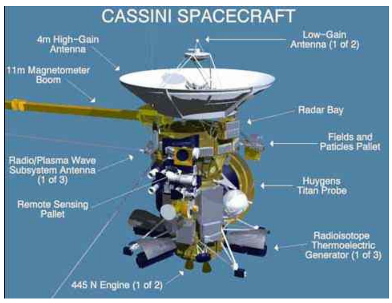


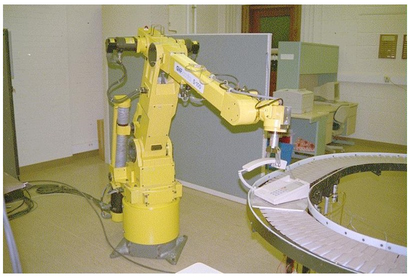
Real-Time Systems





Real-Time Systems





Is there a pattern?

- Hard real-time systems
- Soft real-time systems
- Firm teal-time systems
- Weakly hard real-time

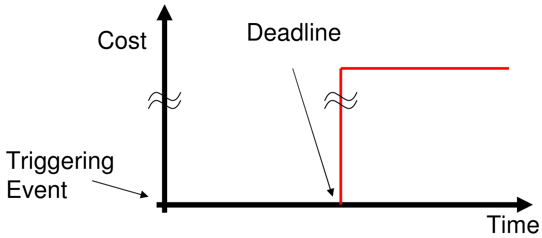
- A deadline is a given time after a triggering event, by which a response has to be completed.
- Therac 25 example

What's needed of an RTOS

- Fast context switches?
  - should be fast anyway
- Small size?
  - should be small anyway
- Quick response to external triggers?
  - not necessarily quick but predictable
- Multitasking?
  - often used, but not necessarily
- "Low Level" programming interfaces?
  - might be needed as with other embedded systems
- High processor utilisation?
  - desirable in any system (avoid oversized system)

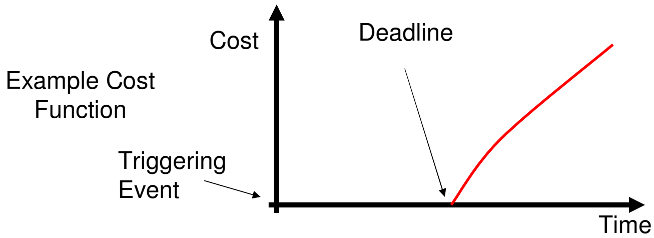
Hard Real-Time Systems

- An overrun in response time leads to potential loss of life and/or big financial damage
- Many of these systems are considered to be safety critical.
- Sometimes they are "only" mission critical, with the mission being very expensive.
- In general there is a cost function associated with the system.



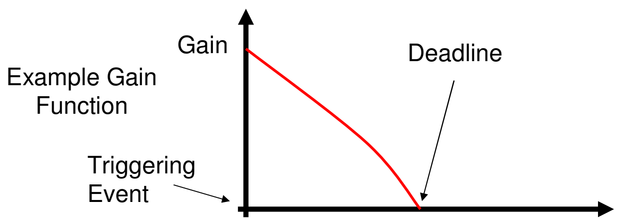
Soft Real-Time

- Deadline overruns are tolerable, but not desired.
- There are no catastrophic consequences of missing one or more deadlines.
- There is a cost associated to overrunning, but this cost may be abstract.
- Often connected to Quality-of-Service (QoS)



Firm Real-Time Systems

- The computation is obsolete if the job is not finished on time.
- Cost may be interpreted as loss of revenue.
- Typical example are forecast systems.



Weakly Hard Real-Time Systems

- Systems where *m* out of *k* deadlines have to be met.
- In most cases feedback control systems, in which the control becomes unstable with too many missed control cycles.
- Best suited if system has to deal with other failures as well (e.g. Electro Magnetic Interference EMI).
- Likely probabilistic guarantees sufficient.

Non Real-Time Systems?

- Yes, those exist!
- However, in most cases the (soft) real-time aspect may be constructed (e.g. acceptable response time to user input).
- Computer system is backed up by hardware (e.g. end position switches)
- Quite often simply oversized computers.

Requirement, Specification, Verification

NICTA

- **Functional requirements**: Operation of the system and their effects.

- **Non-Functional requirements**: e.g., timing constraints.
  - F & NF requirements must be precisely defined and together used to construct the specification of the system.

- A **specification** is a mathematical statement of the properties to be exhibited by a system. It is abstracted such that
  - it can be checked for conformity against the requirement.
  - its properties can be examined independently of the way in which it will be implemented.

Requirement, Specification, Verification

NICTA

- The usual approaches for specifying computing system behavior entail enumerating events or actions that the system participates in and describing orders in which they can occur. It is not well understood how to extend such approaches for real-time constraints.
- F18, therac-25 example

Scheduling in Real-Time Systems

Overview

- Specification and religious believes
- Preemptive vs. non preemptive scheduling
- Scheduling algorithms
- Message based synchronisation and communication
- Overload situations
- Blocking and Priority Inversion

Requirements

- Temporal requirements of the embedded system
  - Event driven
    - Reactive sensor/actuator systems
    - No fixed temporal relation between events (apart from minimum inter arrival times)
  - Cyclic
    - Feedback control type applications
    - Fixed cycles of external triggers with minimal jitter
  - Mixed
    - Anything in between

Specification

- Event triggered systems:
  - Passage of a certain amount of time
  - Asynchronous events
- Time triggered systems:
  - Predefined temporal relation of events
  - Events may be ignored until it's their turn to be served
- Matlab/Simulink type multi rate, single base rate systems:
  - All rates are multiples of the base rate
- Cyclic
  - feedback control loop

Task Model

NICTA

- Periodic tasks
  - Time-driven. Characteristics are known a priori
  - Task τ_i is characterized by (T_i, C_i)
  - E.g.: Task monitoring temperature of a patient in an ICU.
- Aperiodic tasks
  - Event-driven. Characteristics are not known a priori
  - Task τ_i is characterized by (C_i, D_i) and some probabilistic profile for arrival patterns (e.g. Poisson model)
  - E.g.: Task activated upon detecting change in patient's condition.
- Sporadic Tasks
  - Aperiodic tasks with known minimum inter-arrival time (T_i, C_i)

Task Model

NICTA

C_i = Computation time (usually Worst-Case Execution Time, WCET)

D_i = Deadline

T_i = Period or minimum interarrival time

J_i = Release jitter

P_i = Priority

B_i = Worst case blocking time

R_i = Worst case response time

Task Constraints

NICTA

- Deadline constraint
- Resource constraints
  - Shared access (read-read), Exclusive access (write-x)
  - Energy
- Precedence constraints
  - $\tau_1 \Rightarrow \tau_2$: Task τ_2 can start executing only after τ_1 finishes its execution
- Fault-tolerant requirements
  - To achieve higher reliability for task execution
  - Redundancy in execution

Preemption

NICTA

- Why preemptive scheduling is good:
  - It allows for shorter response time of high priority tasks
  - As a result it is likely to allow for a higher utilisation of the processor before the system starts missing deadlines
- Why preemptive scheduling is bad:
  - It leads to more task switches then necessary
  - The overheads of task switches are non-trivial
  - The system becomes harder to analyse whether it is able to meet all its deadlines
  - Preemption delay (cache refill etc.) becomes more expensive with modern processors

Preemption

- Cooperative preemption?
  - Applications allow preemption at given points
  - Reduction of preemptions
  - Increase of latency for high priority tasks

Event Triggered Systems

"... The asynchronous design of the [AFTI-F16] DFCS introduced a random, unpredictable characteristic into the system. The system became untestable in that testing for each of the possible time relationships between the computers was impossible. This random time relationship was a major contributor to the flight test anomalies. Adversely affecting testability and having only postulated benefits, asynchronous operation of the DFCS demonstrated the need to avoid random, unpredictable, and uncompensated design characteristics."

D. Mackall, flight-test engineer AFTI-F16 AFTI-F16 flight tests

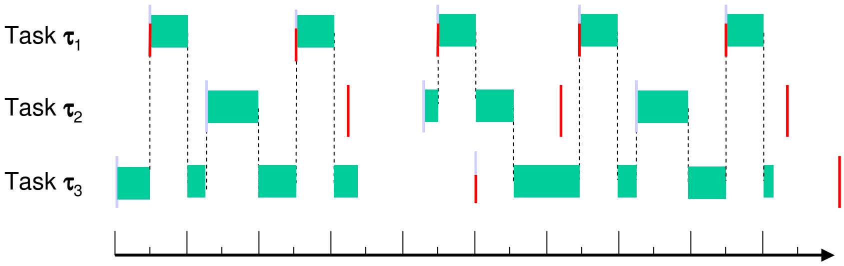
Fixed Priority Scheduling

NICTA

- Priorities may assigned by
  - Deadline: shortest deadline ⇒ highest priority
  - Period: shortest period ⇒ highest priority
  - "Importance"
- Scheduler picks from all ready tasks the one with the highest priority to be dispatched.
- Benefits:
  - Simple to implement
  - Not much overhead
  - Minimal latency for high priority tasks
- Drawbacks
  - Inflexible
  - Suboptimal (from analysis point of view)

Fixed Priority Scheduling(FPS)

NICTA

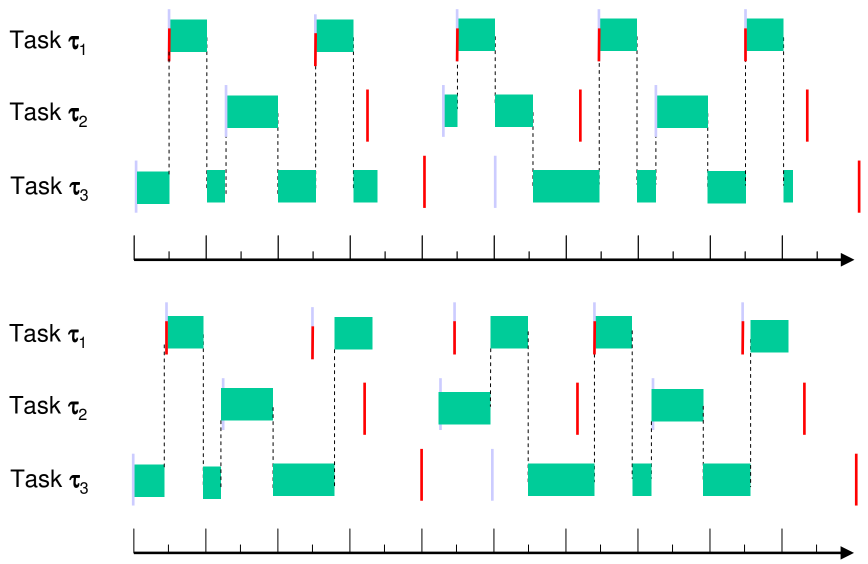


	Priority	C	T	D
Task τ_1	1	5	20	20
Task τ_2	2	8	30	20
Task τ_3	3	15	50	50

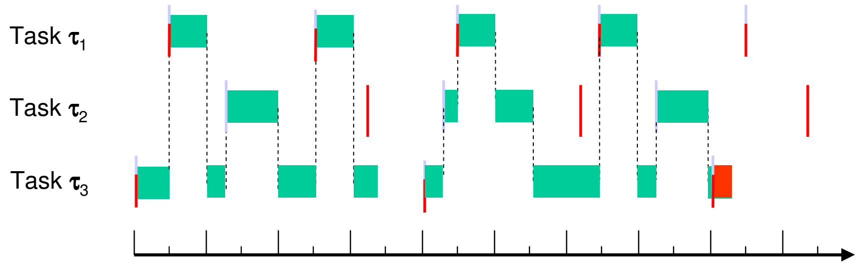
Earliest Deadline First (EDF)

- Dynamic priorities
- Scheduler picks task, whose deadline is due next
- Advantages:
  - Optimality
  - Reduces number of task switches
  - Optimal if system is not overloaded
- Drawbacks:
  - Deteriorates badly under overload
  - Needs smarter scheduler
  - Scheduling is more expensive

FPS vs. EDF

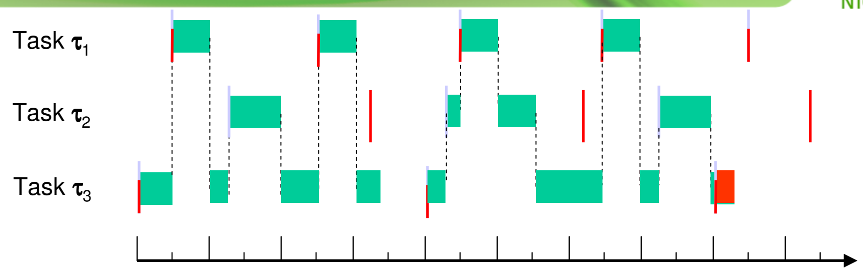


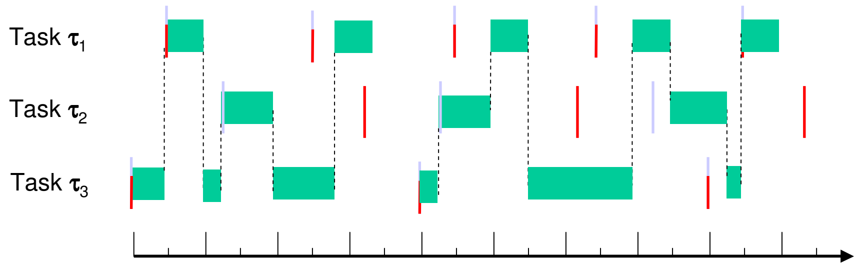
FPS vs. EDF



	Priority	C	T	D
Task τ_1	1	5	20	20
Task τ_2	2	8	30	20
Task τ_3	3	15	40	40

FPS vs. EDF



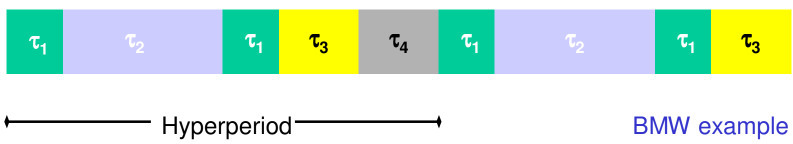


Time Triggered/Driven Scheduling

- Mostly static scheduling
- Time triggered scheduling allows easier reasoning and monitoring of response times
- Can be used to avoid preemption
- Can be used in event triggered systems, but increases greatly the latency
- Most often build around a base rate
- Can be implemented in big executive, using simple function calls

Time Triggered Scheduling

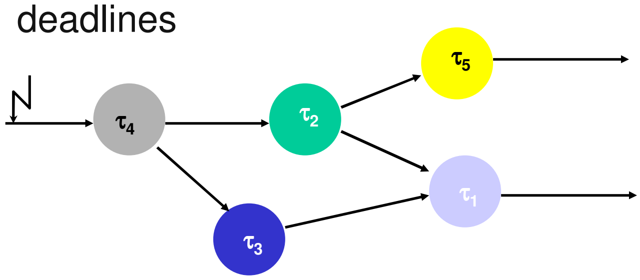
- Advantages:
  - Very simple to implement
  - Very efficient / little overhead (in suitable case)
- Disadvantages:
  - Big latency if event rate does not match base rate
  - Inflexible
  - Potentially big base rate (many scheduling decisions) or hyperperiod



BMW example

Message Based Synchronisation

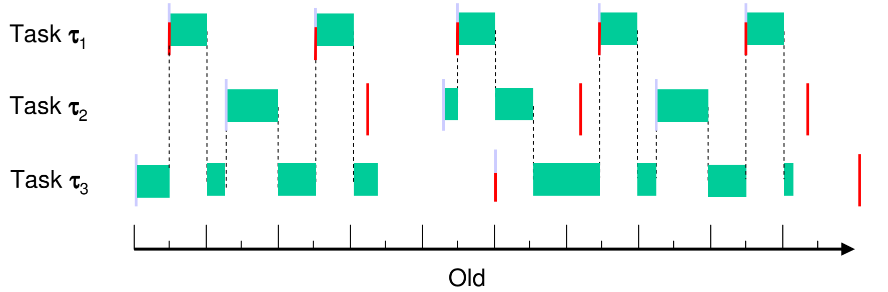
- Tasks communicate via messages
- Task wait for messages (blocked until message arrives)
- Suitable to enforce precedence relations
- Enables messages to be used to transport deadlines



Overload Situations

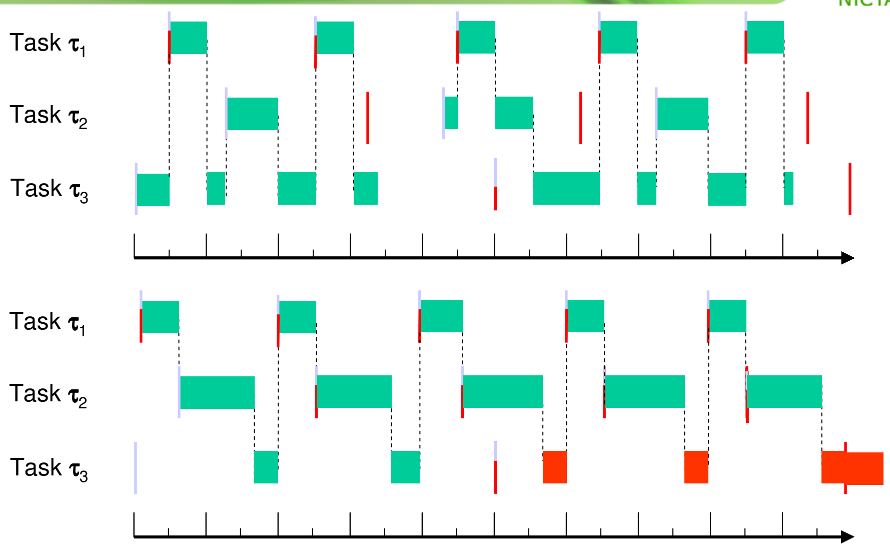
- Caused by faulty components of the system
  - Babbeling idiot or
  - A receiver part erroneously “receiving input”
  - EMI
- Or caused by wrong assumptions regarding the embedding environment
  - Basically wrong event rates or event correlation

Overload Situations in FPS

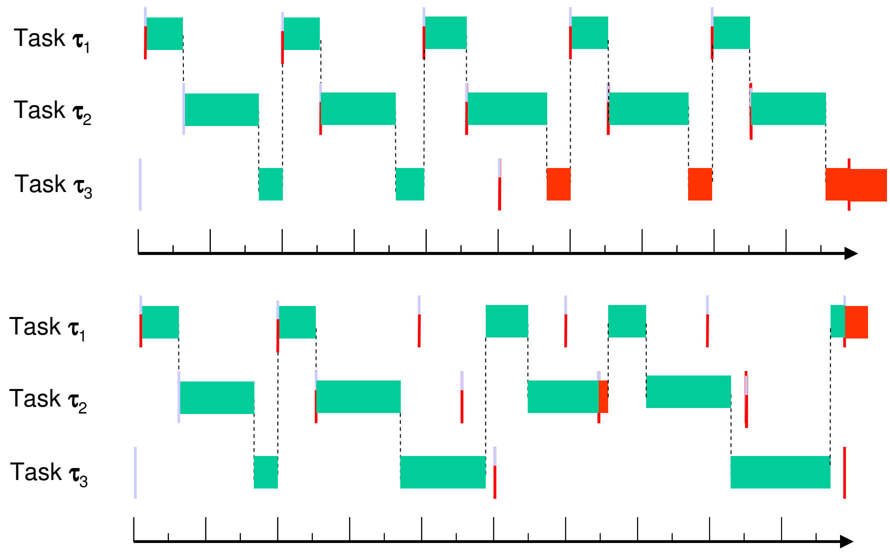


	Priority	C	T	D
Task τ_1	1	5	20	20
Task τ_2	2	12	20	20
Task τ_3	3	15	50	50

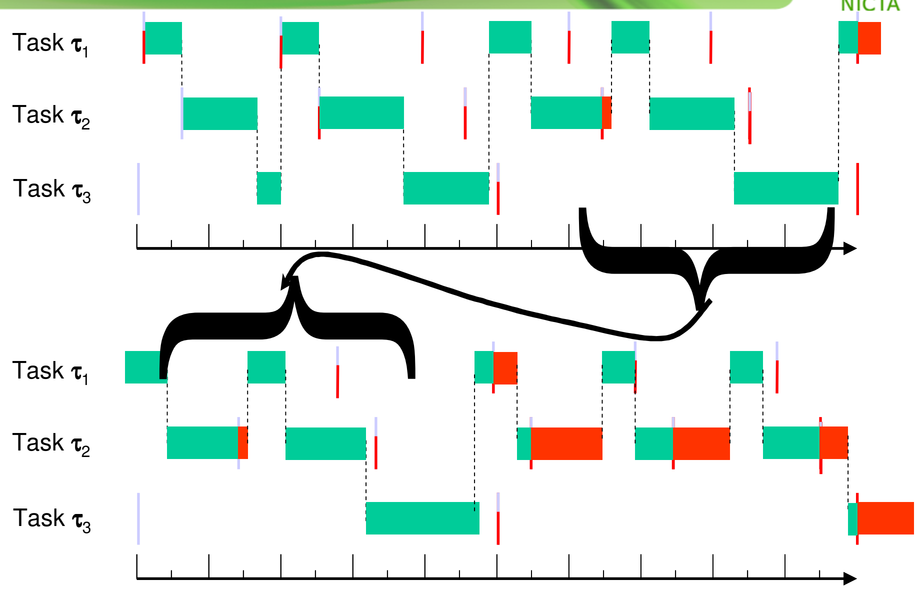
Overload Situations in FPS



Overload Situations in EDF



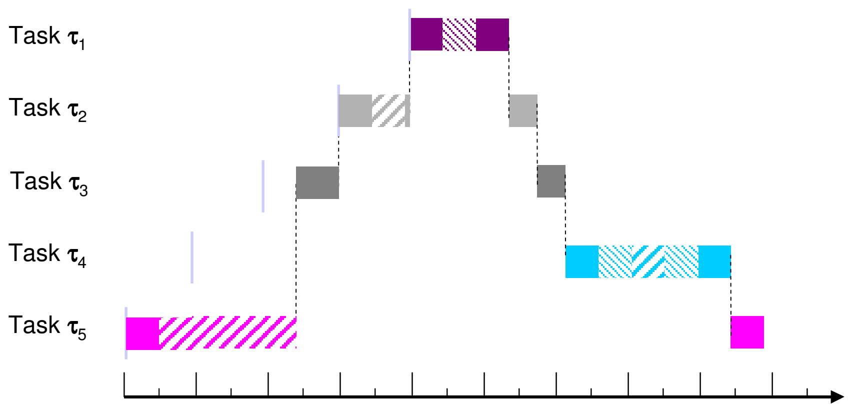
Overload Situations in EDF



Priority Inversion

- Happens when task is blocked in acquiring semaphore from held by lower priority task which is preempted by medium priority task.
- Similar case for server tasks.
- Pathfinder example

Non-Preemptable Critical Sections



- 2 shared resources
- One shared by 3 (nested by one)
- One shared by 2

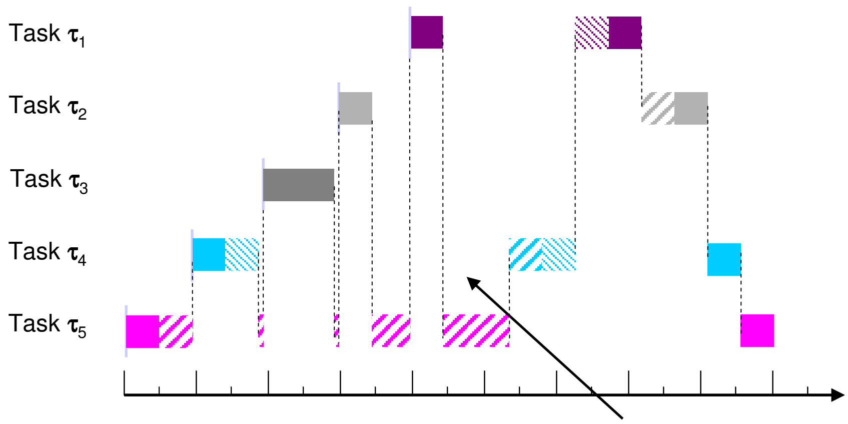
Non-Preemptable Critical Section

NICTA

- GOOD
  - Simple
  - No deadlock.
  - No unbounded priority inversion
  - No prior knowledge about resources.
  - Each task blocked by at most 1 task of lower priority
  - Works with fixed and dynamic priorities. *(especially good for short critical sections with high contention)*
- BAD
  - Tasks blocked even when no contention exists.

Priority Inheritance

NICTA

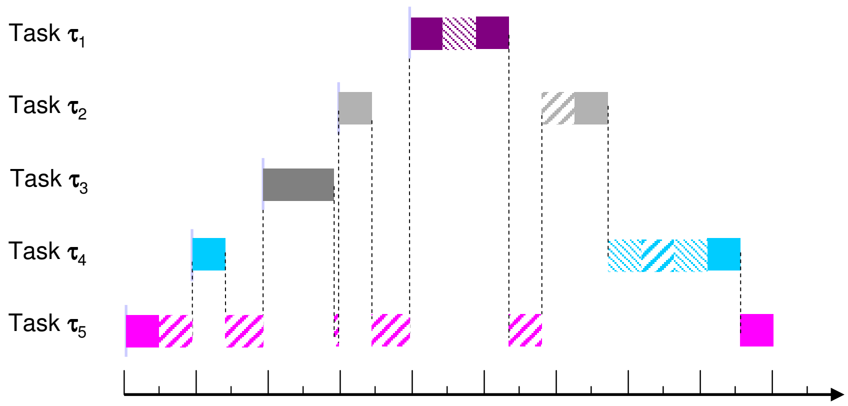


Note the indirect inheritance

Priority Inheritance

- When lower priority job blocks, it inherits priority of blocked job.
- GOOD
  - No unbounded priority inversion
  - Simple
  - No prior knowledge required
  - Works with fixed and dynamic priorities.
- BAD
  - Possible Deadlock.
  - Blocking of jobs not in resource contention.
  - Blocking time could be better
  - Indirection a pain in the neck

Basic Priority Ceiling Protocol



Basic Priority Ceiling Protocol

- Lower priority task inherits priority of blocked task.
- Task may be denied resource even when available.
- Also known as Original Priority Ceiling Protocoll (OPCP)
- GOOD
  - No deadlock.
  - No unbounded priority inversion.
  - Blocking time reduced.
- BAD
  - Task may be denied resource even when available.
  - Need *a priori* knowledge of use of resources.

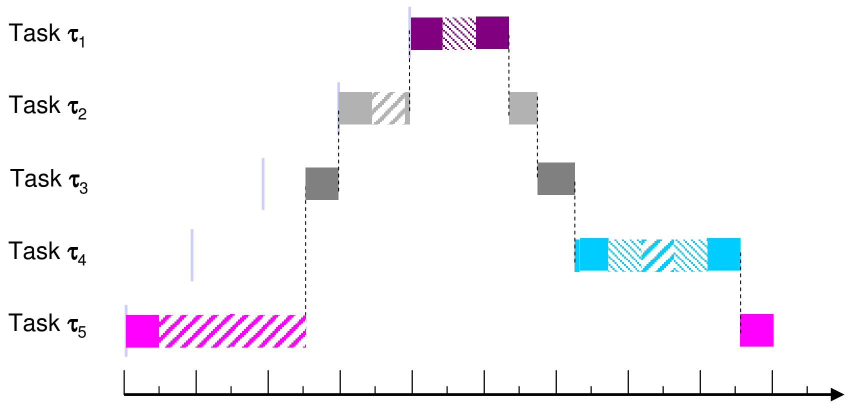
$$B_i = \max_{k=1}^{K} usage(k,i)C(k)$$

Basic Priority Ceiling

$$B_i = \sum_{k=1}^{K} usage(k,i)C(k)$$

Priority Inheritance

Immediate Priority Ceiling Protocol



Immediate Priority Ceiling Protocol

NICTA

- Lower priority task inherits priority of potentially blocked task. Task may be denied resource even when available.
- GOOD
  - Simple.
  - Shared run-time stack.
  - Reduced Context-Switching
  - No deadlock.
  - No unbounded priority inversion.
- BAD
  - Task may be denied resource even when available
  - Task may be affected by blocking effect without using any resources
  - Need *a priori* knowledge of use of resources.
  - No self suspension while holding a resource

Implementation Comparison

NICTA

- Non-preemptable critical sections
  - Easy to implement. Either blocking interrupts or syscall to have that implemented on behalf of task
- Priority Inheritance
  - Fairly straightforward, however requires various references (e.g. which thread is holding a resource)
- Basic Priority Ceiling
  - Requires application designer to explicitly identify which resources will be requested later (when first resource request of nested requests is made) on top of references
- Immediate priority ceiling
  - Very easy to implement: Only requires ceilings associated with each resource mutex (that's something which may be automated if all tasks known
  - Alternatively server task encapsulating the critical section

Reflective/Feedback-based Scheduling

NICTA

- Adaptive systems
- By definition soft real time
- Adjusts scheduling based on information about change
- Capable of better coping with “the unknown”
- Connects quite well with adaptive applications

NICTA

THE UNIVERSITY OF NEW SOUTH WALES

Schedulability Analysis of Real-Time Systems

Schedulability Analysis

NICTA

- Tries to establish, whether the task system described is actually schedulable
  - In the classical sense this is, whether all the deadlines are met under all circumstances;
  - Recent move to satisfaction of Quality-of-Service constraints;
- Relies on availability of computation time of tasks
  - WCET;
  - Execution time profiles.

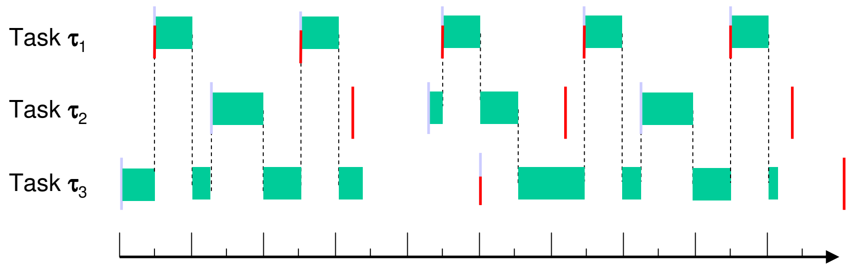
Critical Instant

NICTA

- Trivial for independent tasks
  - All events happen at the same time;
  - However, implicitly consider all possible phases (take nothing for granted).
- However, get’s more tricky (but tighter) having dependencies
  - What phasing of other activities produces the biggest load.
  - An activity is a string of tasks triggered by a single event.

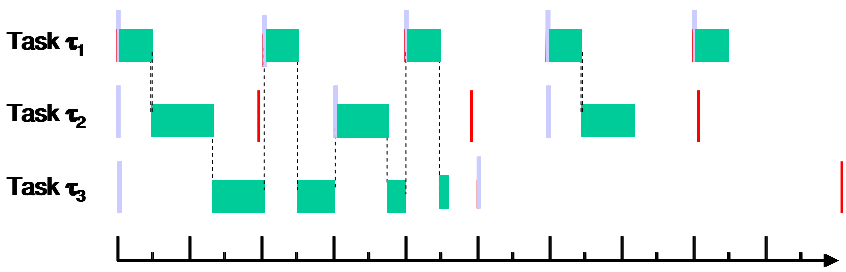
Response Time Analysis

- Does not directly consider deadlines
- Makes the assumption of jobs being executed in order
- Usually used in fixed priority systems



Response Time Analysis

	Priority	C	T	D
Task τ_1	1	5	20	20
Task τ_2	2	8	30	20
Task τ_3	3	15	50	50



Formal RTA

NICTA

- Assumptions j<i ⇒priority j is lower than priority i
- Critical instant
- Iterative process

$$w_i^0 = C_i$$

$$w_i^{n+1} = C_i + \sum_{\forall j<i} \left\lceil \frac{w_i^n}{T_j} \right\rceil * C_j$$

Blocking Time and Other Nasties

NICTA

- Blocking time
- Jitter
- Pre-emption delay

$$w_i^{n+1} = C_i + B_i + \sum_{\forall j<i} \left\lceil \frac{J_j + w_i^n}{T_j} \right\rceil * (C_j + \delta_{i,j})$$

Rate Monotonic Analysis

NICTA

- Looks at *utilisation* do determine whether a task is schedulable
- Initial work had following requirements:
  - All tasks with deadlines are periodic
  - All tasks are independent of each other (there exists no precedence relation, nor mutual exclusion)
  - $T_i = D_i$
  - C_i is known and constant
  - Time required for context switching is known

Rate Monotonic Analysis contd

NICTA

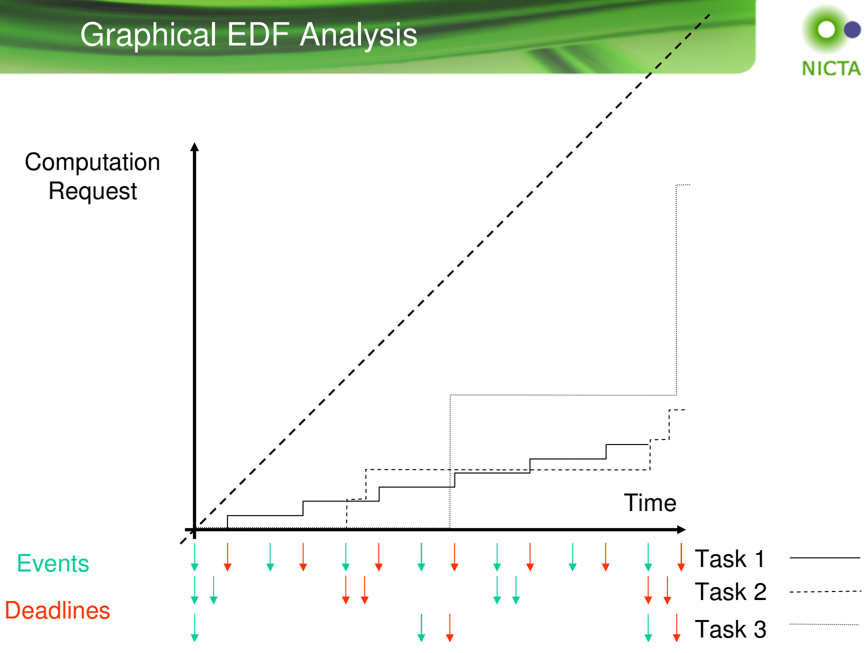
- Bound is given by:

$$\mu = \sum_{\forall i} \left[\frac{C_i}{T_i} \right] \leq n * (2^{1/n} - 1)$$

- Has been relaxed in various ways, but still it is only an approximate technique.
- Further info can be found here: http://www.heidmann.com/paul/rma/PAPER.htm

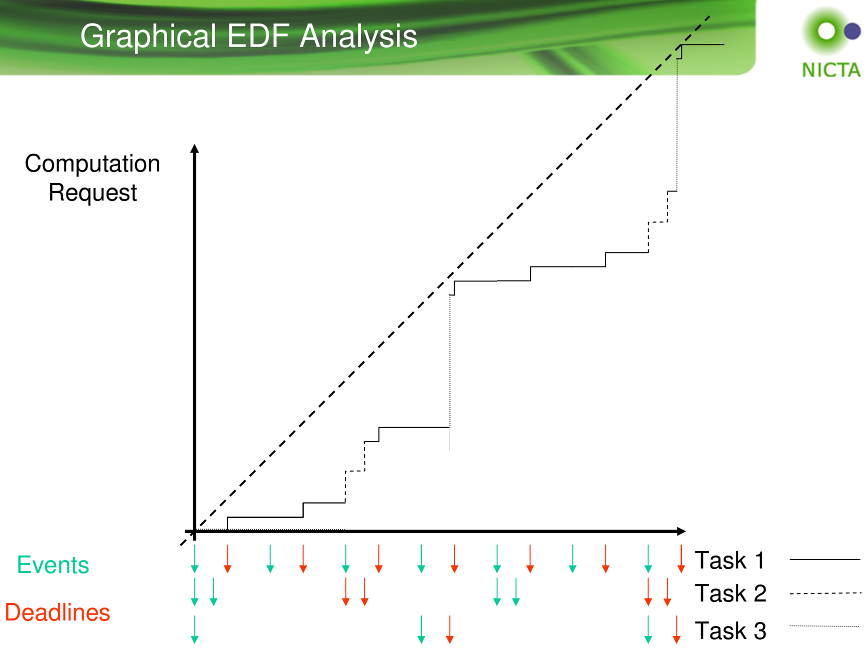
Graphical EDF Analysis

NICTA



Graphical EDF Analysis

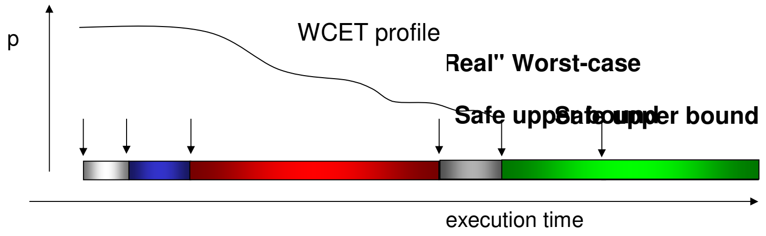
NICTA



Worst Case Execution Time Analysis

Problem Definition

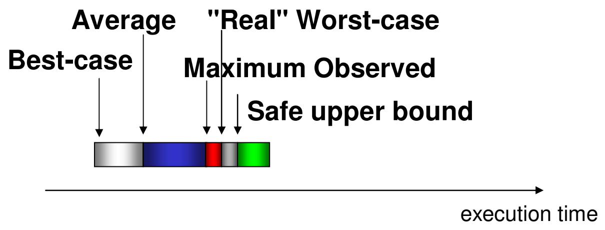
- All of the scheduling analysis presented previously requires the Worst-Case Execution time to be known
- Target is to come up with
  – a safe upper bound
  – as close as possible to the "real" worst case.
  – Ideally with more than just single number (probabilistic analysis)



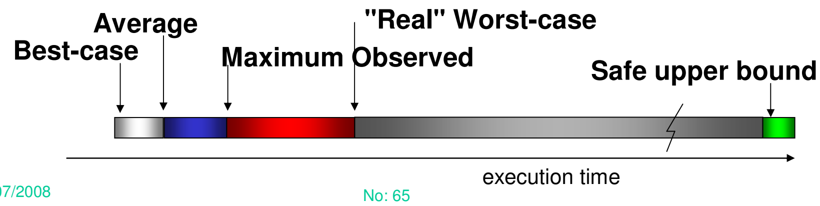
Problem Definition contd

NICTA

Simple Code + Simple Processors



Complex Code + Advanced processors



Is it a Problem?

NICTA

- Safety critical computer systems exist and are deployed
- Yes, but …
  - Safety critical systems have been
    - highly restrictive in terms of HW/SW used
    - highly restrictive in terms of complexity
    - used a lot of manual inspection and pen and paper work

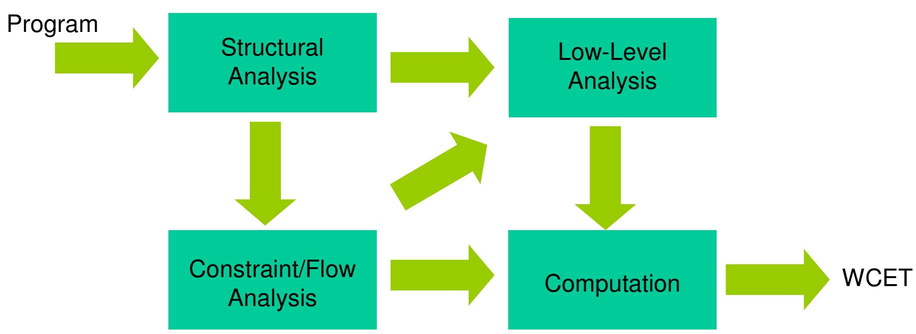
Is it a Problem? contd

- The stuff in the last slide doesn't scale!
- industry not in the safety critical arena have been using measurements with safety factors.
  - Worked fine with simple architectures, but doesn't work good with more advanced computers
  - Excessive overestimation and underestimation with same factor for different programs, parameterisation doesn't help too much

- Large body of academic work, but little industrial uptake: **YET**

Generic Problem Partitioning

- Some analysis methods integrate some aspects of these, but the general requirements are the same



Structural Analysis

- Can work on:
  - Source code and/or
  - Object code or
  - Assembly Code

Structural Analysis contd

- Object Code
  - Pros:
  - All compiler optimisations are done
  - This is what really is running, no trouble with macros, preprocessors
  - Cons:
  - Needs to second guess what all the variables *meant*
  - A lot of the original information is lost
    - E.g. multiple conditions, indirect function calls, object member functions

Structural Analysis contd

NICTA

- Assembly Code
  - Pros:
  - All compiler optimisations done
  - Cons:
  - Same as Object Code +
  - Potentially still some macros

Structural Analysis contd

NICTA

- Source Code
  - Pros:
  - All information the user has put there is there
  - Structure in pure form (e.g. multiple loop continue conditions, object member functions, indirect calls)
  - Cons:
  - Trouble with macros, preprocessors etc.
  - Needs to second guess what the compiler *will do*

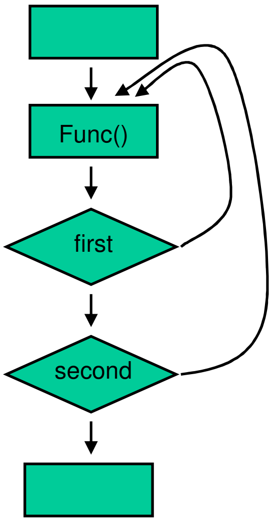
© NICTA 2007/2008

Multiple Continue conditions explained

```
for (; first condition || other cond;){
    Func();
}
```

May look like

```
for (; first condition;){
    for (; other cond;){
        Func();
    }
}
```



Flow information

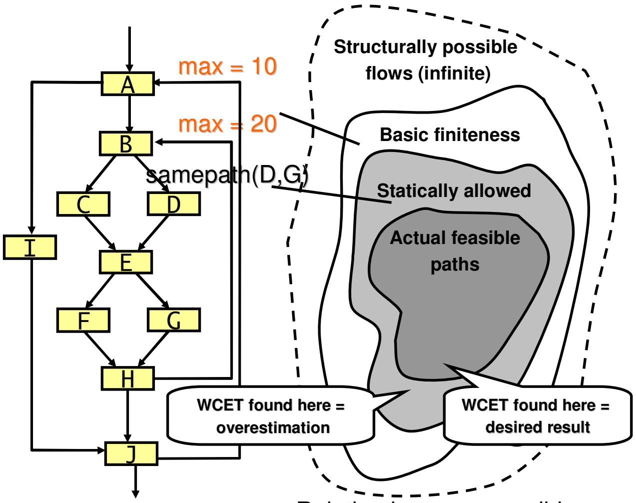
- For low level analysis and computation we need to restrict flow to reasonable subset.
- This information can be gained:
  - By static analysis (most importantly abstract interpretation)
  - By observation (worst case?)
  - By user annotations

Flow Info Characteristics

NICTA

```
do
{
  if(...)        // A
     do
     {
       if(...)      // B
          ...       // C
       else
          ...    // D
       if(...)     // E
          ...   // F
       else
          ...   // G
     } while(...) // H
  else
     ...     // I
} while(...)   // J
...
```

Example program



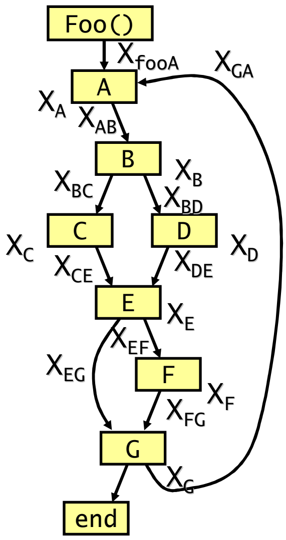
Basic block graph

Relation between possible executions and flow info

Constraints Generated

NICTA

- Constraints:
  - **Start and end condition** — $X_{foo}=1$, $X_{end}=1$
  - **Program structure** — $X_A=X_{fooA}+X_{GA}$, $X_{AB}=X_A$, $X_{BC}+X_{BD}=X_B$, $X_E=X_{CE}+X_{DE}$
  - **Loop bounds** — $X_A<=100$
  - **Other flow information** — $X_C+X_F<=X_A$



Hardware

- WCET analysis requires a deep understanding of
  - hardware features of processors
  - Interaction of software and hardware

Static Analysis

- Looking at basic blocks in isolation (tree based, IPET based)
  - Problem of caching effects
- Path based analysis: popular but very expensive
- Problem of conservative assumptions
- Hardware analysis is very expensive
  - Data caches and modern branch prediction are very hard to model right.
  - Call for simpler hardware, e.g. scratchpad memory instead of caches

Measurement Based Analysis

- End-to-end measurements + safety factor used for industrial soft-real time system development
  - Failed for modern processors as WC could hardly be expressed as function of AC
- Measurement on basic block level
  - Safer than end-to-end measurements but potentially very pessimistic
- What is the worst-case on HW?
- Can it be reliably produced?
- What about preemption delay?

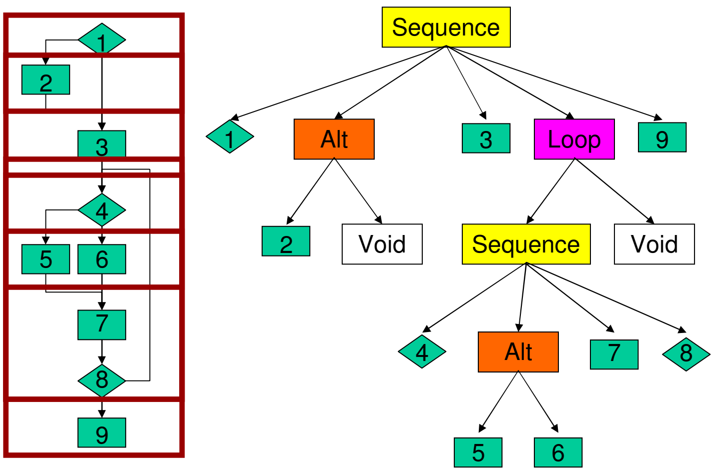
Path Based Computation

- Follows each individual paths
- Becomes quickly intractable for large applications
- Altenbernd and Co have tried a simplified approach:
  - Starting out from the entry point of a function follow a path in the CFG and annotate each node with the execution time up to this node
  - Do so with any other path, but whenever a join node is reached compare new value up to this point with annotated value

Path Based Computation

- Continue if new value is larger or not smaller than the the old value minus the smallest of the largest 5 overall execution times paths computed so far. (otherwise start next path)
- If overall path is larger than smallest of the largest 5 overall execution times, keep (remove the compared smallest of the largest 5 overall execution time paths.
- Check feasibility of 5 longest paths (path may actually happen)

Tree Representation



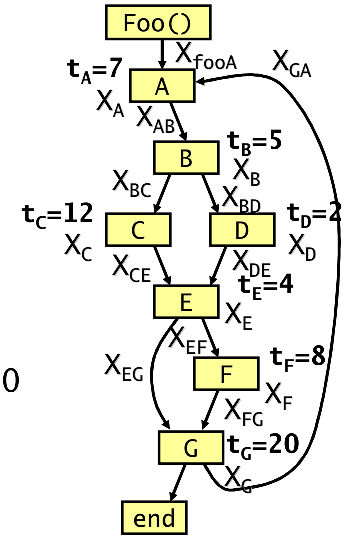
IPET Calculation

NICTA

- WCET=

  max $\Sigma(x_{entity} * t_{entity})$

  – Where each x_{entity} satisfies all constraints



$X_{foo}=1$ $\quad X_A=X_{fooA}+X_{GA}$ $\quad X_C+X_F=100$

$X_{AB}=X_A$

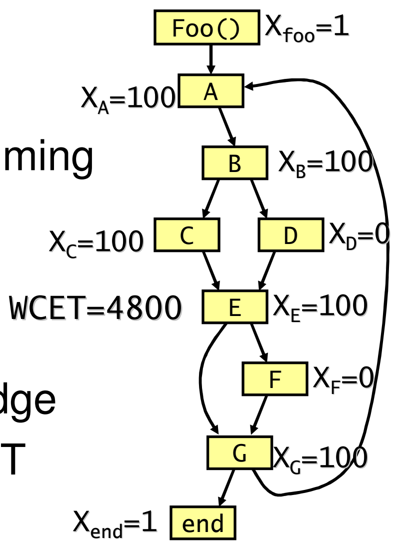
$X_{BC}+X_{BD}=X_B$ $\quad X_A<=100$

$X_E=X_{CE}+X_{DE}$

Calculation methods

NICTA

- Solution methods:
  – Integer linear programming
  – Constraint satisfaction
- Solution:
  – Counts for each individual node and edge
  – The value of the WCET



Multiprocessor/Multithreaded Real-Time Systems

WHY

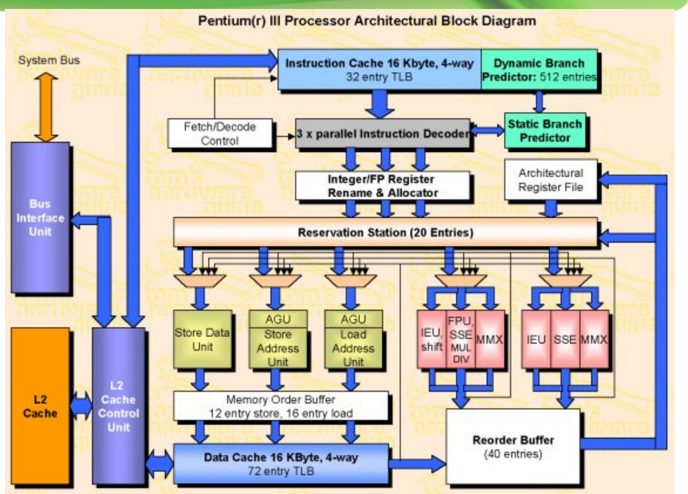
- Performance
  - Responsiveness in the presence of many external events
- Throughput
  - Managing continuous load
- Fault tolerance
  - Managing bugs, HW faults
- Reliability
  - Ensuring uptime, HW/SW upgrades …

NICTA

- Symmetric Multithreading (SMT)
  - Contention on execution units, caches, memory
- Symmetric Multiprocessor (SMP)
  - Contention on memory, cache coherency, eg NUMA
- Asymmetric Multiprocessor
  - Specialised units, coherency

- Distributed System
  - Latency in communication, loosely coupled

NICTA



Almost an SMT:

Image taken from http://www.tommesani.com/images/P3Architecture.jpg

SMP

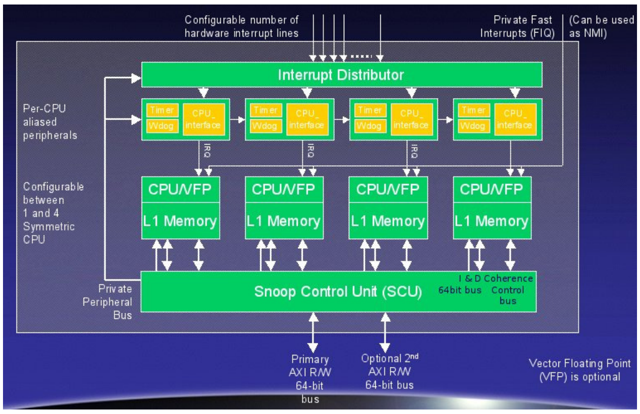
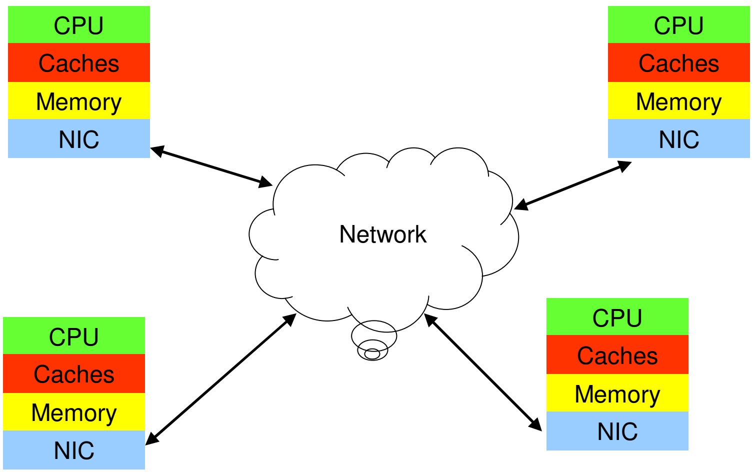


Image taken from http://linuxdevices.com/files/misc/arm-mpcore-architecture-big.jpg

Distributed System



Issues

- Resource contention
  - Execution units
  - Caches
  - Memory
  - Network
- Adding a CPU does not help
  - Example double the load, 2 instead of 1 CPU

Solutions??

- Partitioning
  - Resource contention still there!
  - Assignment using heuristics
- Non partitioning
  - mostly theoretical so far
  - Assumptions:
    - Zero preemption cost
    - Zero migration cost
    - Infinite time slicing
  - Don’t translate into reality
  - Acceptance test and no task migration a way to make it work

Solutions??

NICTA

- Quite often non-preemptive
  - Fewer context switches
  - Reasoning is easy
    - IEEE Computer reference to insanity
  - Testing is easier??
  - Reduce need for blocking
- But!

Non-Preemptive

NICTA

- But!!!
  - Less efficient processor use
  - Anomalies: response time can increase with
    - Changing the priority list
    - Increasing number of CPUs
    - Reducing execution times
    - Weakening the precedence constraints
  - Bin packing problem NP hard
  - Theoretically: time slicing into small quantums (PFAIR), but practically useless, as preemption and task migration overhead outweigh gains of Multiprocessors.

And now?

NICTA

- No global solution.
- Partitioning and reducing it to single CPU problem good, but still contention of resources.
- Next step: After figuring out how to do the scheduling, what about preemption delay?
- Industry works with SMP/SMT, but most often on a very ad hoc basis.
- Active and unsolved research area
- Why does it work on non-RT?
  – Running the “wrong” task is not critical.

NICTA

Integrating Real-Time and General-Purpose Computing

Many thanks to: Scott A. Brandt

University of California, Santa Cruz

Real-Time vs. General-Purpose OS

- Real-time and general-purpose operating systems implement many of the same basic operations
  - Process mgmt., memory mgmt, I/O mgmt, etc.
- They aim for fundamentally different goals
  - Real-time: Guaranteed performance, timeliness, reliability
  - General-purpose: Responsiveness, fairness, flexibility, graceful degradation, rich feature set
- They have largely evolved separately
  - Real-time system design lags general-purpose system design by decades
- They need to merge

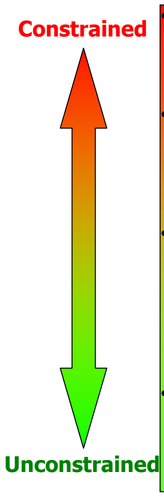
Why?

- We want both flexible general-purpose processing and robust real-time processing
  - Multimedia is ubiquitous in general-purpose systems
  - Real-time systems are growing in size and complexity
- Such systems are possible
  - Look at the popularity of RTLinux
  - GP hardware has grown powerful enough to support traditional hard real-time tasks (multimedia, soft modems, etc.)
  - Windows, MacOS, etc., are already headed in this direction
- Existing solutions are *ad hoc*
  - RTLinux, MacOS, Windows?
- The world is already headed that way
  - Microsoft, HP, Intel, Dell all want to develop integrated home systems
  - Complex distributed real-time systems do more than hard real-time
- We need to get out in front and lead the way

How?

- We need integrated solutions for each type of resource
  - CPU, storage, memory, network, …
- They must be hard real-time at their core
  - This is the only way to guarantee the hardest constraints
- They must provide native hard real-time, soft real-time, and best-effort support
  - SRT and BE support cannot be added as an afterthought
  - Neither can HRT
- We need an overall model for managing the separate resources
  - Each process must be able to specify it's per-resource constraints
  - Defaults should be reasonable, and helpful

Kinds of Timeliness Requirements



- Hard Real-Time (HRT) [e.g. flight control]
  - Hard deadlines, WCET
- Rate-Based (RB) [e.g. desktop audio]
  - Continuous processing requirements
- Soft Real-Time (SRT) [e.g. desktop video]
  - Non-critical deadlines and/or variable processing needs, worst-case, average-case, or no estimates
- Best Effort (BE) [e.g. editor or compiler]
  - Undefined timeliness requirements

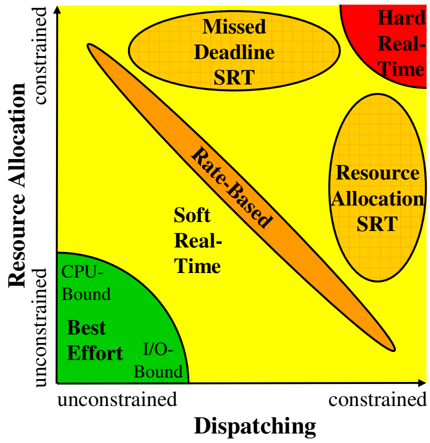
- We want to run processes with different timeliness requirements in the same system
  - HRT, RB, SRT, and BE
- Existing schedulers largely provide point solutions:
  - HRT **or** RB **or** one flavor of SRT **or** BE
- Hierarchical scheduling is a partial solution
  - Allows apps with a variety of timeliness requirements, BUT
  - Static, inflexible hierarchies
- Goal: Uniform, fully dynamic integrated real-time scheduling
  - Same scheduler for all types of applications

Separate Resource Allocation and Dispatching

- Observation: Scheduling consists of two distinct questions:

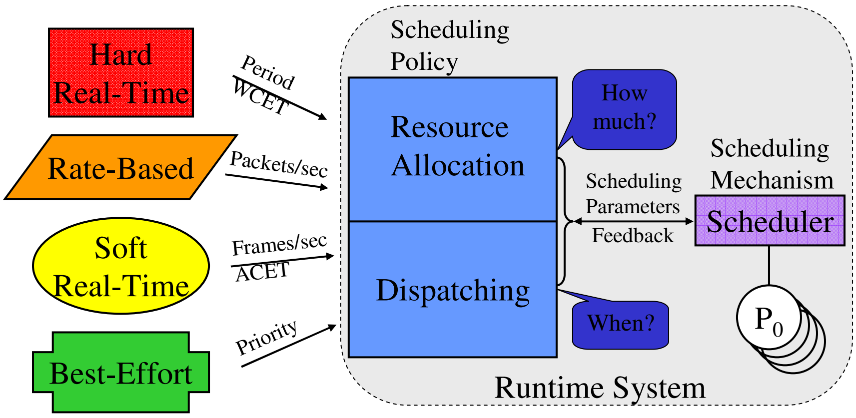
  Resource allocation
  - *How much* resources to allocate to each process

  Dispatching
  - *When* to give each process the resources it has been allocated
- Existing schedulers integrate their management
  - Real-time schedulers implicitly separate them somewhat via job admission



The (RAD) Scheduling Model

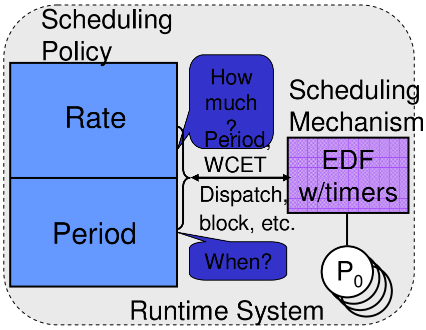
- Separate management of Resource Allocation and Dispatching
  - and separate policy and mechanism



Rate-Based Earliest Deadline Scheduler

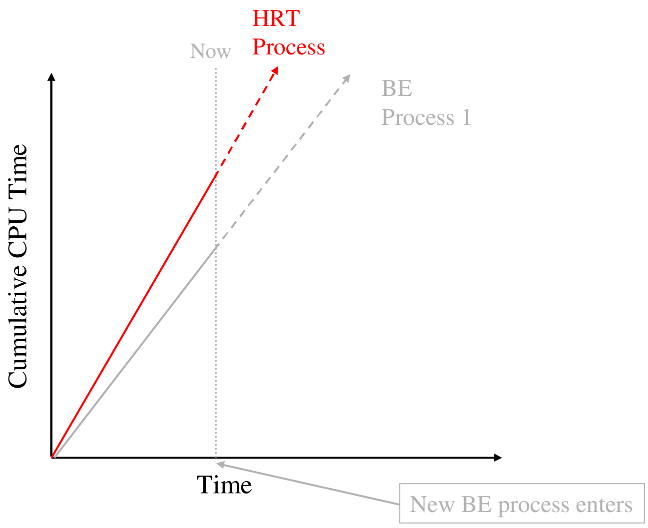
- Basic Idea
  - EDF provides hard guarantees
  - Varying rates and periods provide flexibility
  - Programmable timer interrupts guarantee isolation between processes
- RBED policy
  - Resource allocation: Target rate-of-progress for each process (S ≤ 100%)
  - Dispatching: Period based on process timeliness needs
- RBED mechanism
  - Rate-Enforcing EDF: EDF + programmable timer interrupts

RBED: RAD Scheduler using *rate* and *period* to control resource allocation and dispatching

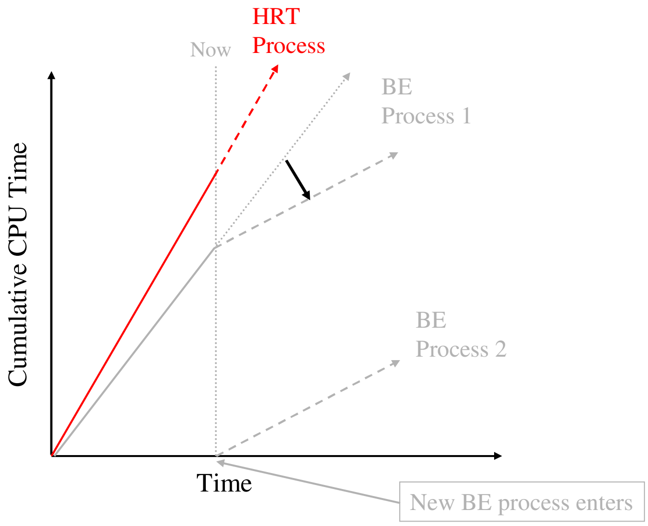


rate = utilization
WCET = rate*period

Adjusting Rates at Runtime



Adjusting Rates at Runtime



RBED Periodic Task Model

EDF

- Period and WCET are specified per task
  - T_i has sequential jobs $J_{i,k}$
  - $J_{i,k}$ has release time $r_{i,k}$, period p_i, deadline $d_{i,k}$
  - $r_{i,k} = d_{i,k-1}$, and $d_{i,k} = r_{i,k} + p_i$
  - $u_i = e_i/p_i$ and $U = \Sigma\, u_i$

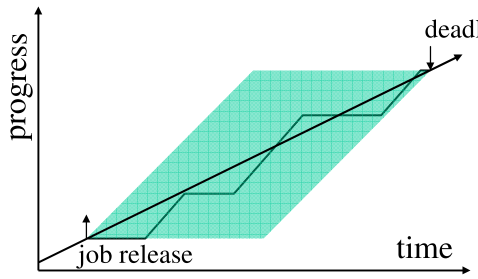
RBED

- Period and WCET are specified per job
  - T_i has sequential jobs $J_{i,k}$
  - $J_{i,k}$ has release time $r_{i,k}$, period $p_{i,k}$, deadline $d_{i,k}$
  - $r_{i,k} = d_{i,k-1}$, and $d_{i,k} = r_{i,k} + p_{i,k}$
  - $u_{i,k} = e_{i,k}/p_{i,k}$ and $U = \Sigma u_{i,k}$

- Theorem 1: *EDF is optimal under the new task model*
  - Corollary: *A new task may enter the system at any time, as long as resources are available for it*

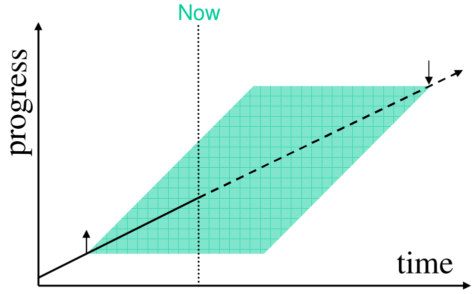
Two Observations

- At deadlines, a task's actual resource allocation is equal to its target resource allocation
- Actual resource allocation is bounded to the *feasible region*



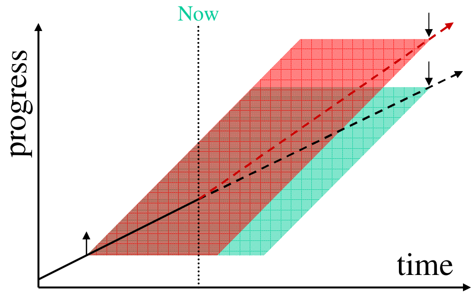
Increasing Rate (= increasing WCET)

- Theorem 2: *The resource usage of any task can be increased at any time, within the available resources*
  - Given a feasible EDF schedule, at any time task T_i may increase utilization by any amount up to $1–U$ without causing any task to miss deadlines in the resulting EDF schedule



NICTA

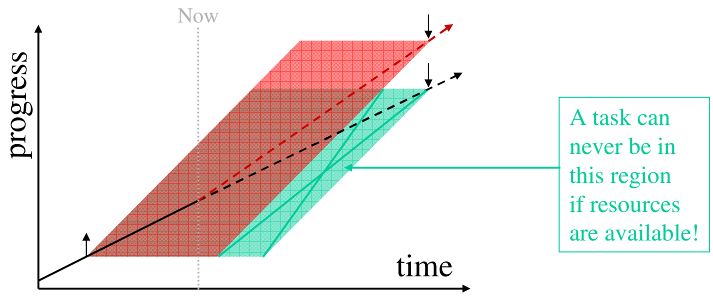
- Theorem 2: *The resource usage of any task can be increased at any time, within the available resources*
  - Given a feasible EDF schedule, at any time task T_i may increase utilization by any amount up to $1-U$ without causing any task to miss deadlines in the resulting EDF schedule



Increasing Rate (= increasing WCET)

NICTA

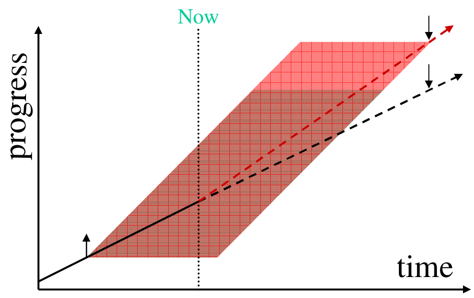
- Theorem 2: *The resource usage of any task can be increased at any time, within the available resources*
  - Given a feasible EDF schedule, at any time task T_i may increase utilization by any amount up to $1-U$ without causing any task to miss deadlines in the resulting EDF schedule



Increasing Rate (= increasing WCET)

NICTA

- Theorem 2: *The resource usage of any task can be increased at any time, within the available resources*
  - Given a feasible EDF schedule, at any time task *Ti* may increase utilization by any amount up to *1–U* without causing any task to miss deadlines in the resulting EDF schedule



RBED EDF Mode Change Theory

NICTA

- Theorem 1: *EDF is optimal under this task model*
- Corollary: *A new task may enter at any time, within available resources*
- Theorem 2: *The rate of any task can be increased at any time, within available resources*
- Theorem 3: *The period of any task can be increased at any time*
- Theorem 4: *The rate of any task can be lowered at any time, down to what it has already used in the current period*
- Theorem 5: *The period of any task can be reduced at any time, down to the time corresponding to the current period's resource usage*
- Corollary: *The period of any task can be increased at any time (without changing WCET)*
- Corollary: *The period of a job which is ahead of its target allocation can be reduced at any time, down to the time corresponding to its current resource usage (without changing WCET) as long as the resources are available for the rate change*

RBED Theory Summary

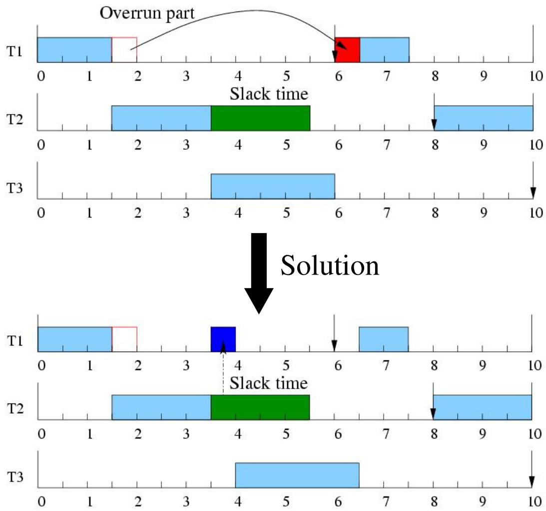
- Rate and period can be changed without causing missed deadlines
  - At deadlines, rate and period changes are unconstrained (except by available resources)
  - In between, decreases are constrained by resource usage in the current period
  - The changes may be combined

- Isolation between processes is guaranteed

Better Slack Management: BACKSLASH

- Existing algorithms tend to ignore the needs of “background” tasks
  - Slack provided when everything else is idle
  - Aim for “fair” allocation and 100% utilization
- Slack reclamation is critical in an integrated real-time system
  - Utilization is important for best-effort systems
  - Soft real-time and best effort performance depends on the effective use of slack
- BACKSLASH improves performance via slack scheduling
  - Focuses on when slack is allocated, and to which process

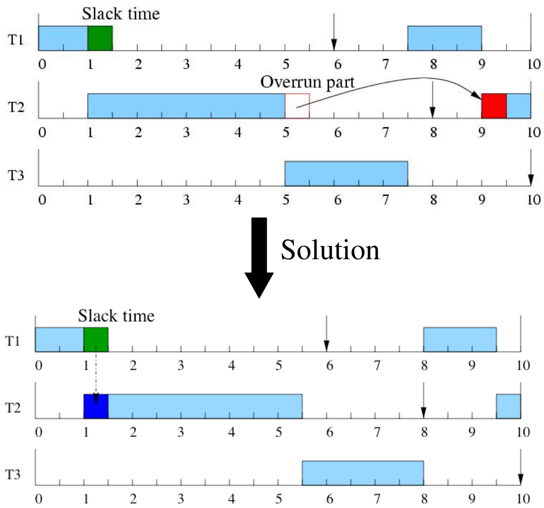
When To Allocate Slack?



Task	Reservation	Period
T1	1.5	6.0
T2	4.0	8.0
T3	2.5	10

Answer: Allocate slack as early as possible

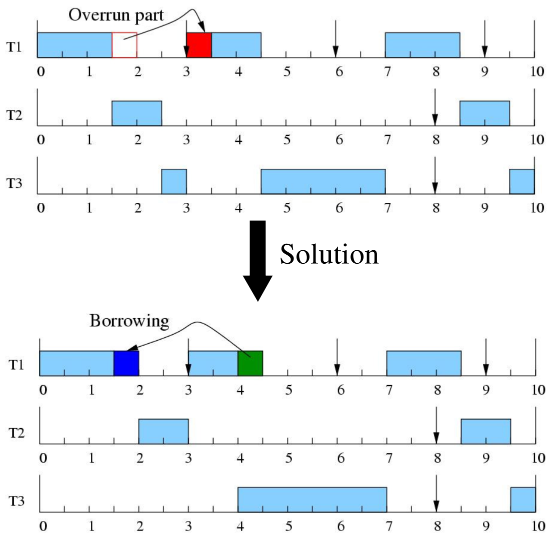
Who To Allocate Slack To?



Task	Reservation	Period
T1	1.5	6.0
T2	4.0	8.0
T3	2.5	10

Answer: Allocate slack to the task with the earliest deadline

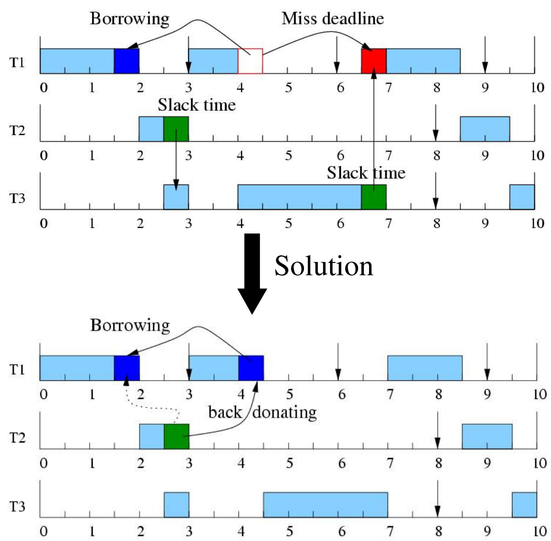
How To Use Future Slack?



Task	Reservation	Period
T1	1.5	3.0
T2	1.0	8.0
T3	3	8

Answer: Borrow resources (potential slack) from the next job to meet the current deadline

How to Allocate Slack to Past Overruns?



Task	Reservation	Period
T1	1.5	3.0
T2	1.0	8.0
T3	3	8

Answer: Back-donate slack to tasks that borrowed from the future

Principles

NICTA

1. Allocate slack as early as possible
   - With the priority of the donating task
2. Allocate slack to the task with highest priority (earliest original deadline)
   - *Task* deadline, not *server* deadline
3. Allow tasks to borrow against their own future resource reservations to complete their current job
   - With the priority of the donating job
4. Retroactively allocate slack to tasks that have borrowed from their current budget to complete a previous job

SRAND

+

SLAD

+

SLASH

+

BACK SLASH

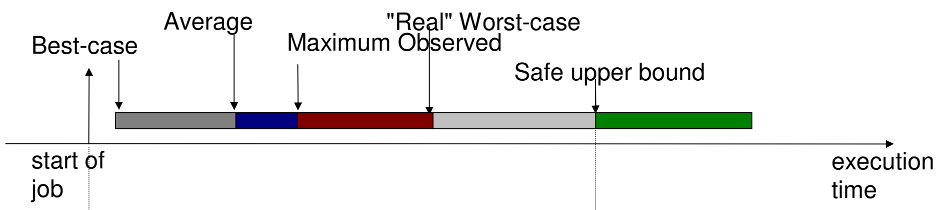
BACKSLASH Conclusions

NICTA

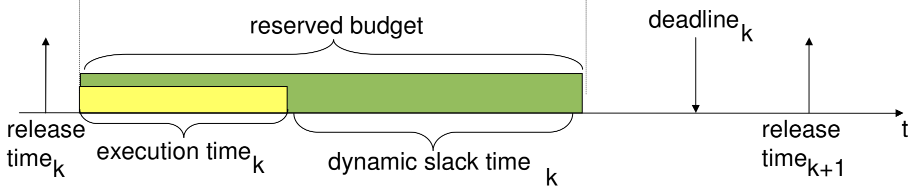
- In an integrated system supporting HRT, SRT and BE, the performance of SRT (and BE) depends on the effective reclamation and distribution of slack
- Four principles for effective slack reclamation and distribution:
  1. Distribute slack as early as possible
  2. Give slack to the ready task with the highest priority
  3. Allow tasks to borrow against future reservations
  4. Retroactively give slack to tasks that needed it
  5. SMASH: Conserve slack across idle times!
- Our results show that these principles are effective: BACKSLASH significantly outperforms the other algorithms and improves SRT (and/or BE) performance

Bandwidth Enforcement in RBED and Power Management

NICTA



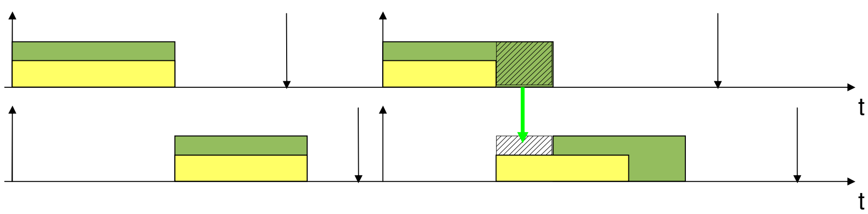
Task model



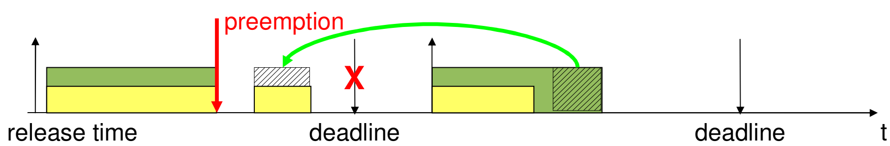
Some Slack Management in SLASH

NICTA

Dynamic slack donation

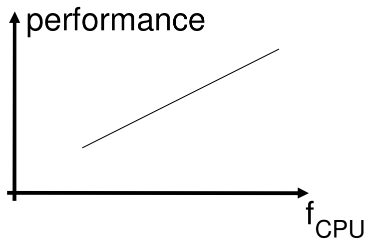


Future Slack Borrowing

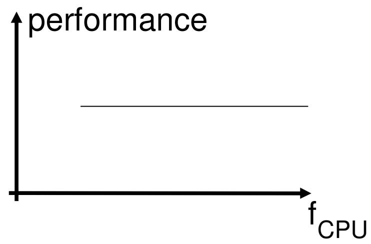


Modelling Time

NICTA



CPU bound application



Memory bound application

$$T = \frac{C_{cpu}}{f_{cpu}} + \frac{C_{mem}}{f_{mem}} + \frac{C_{bus}}{f_{bus}} + \ldots$$

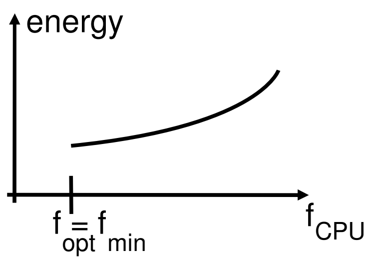
$$C_{mem} = \alpha_1 PMC_1 + \alpha_2 PMC_2 + \ldots$$

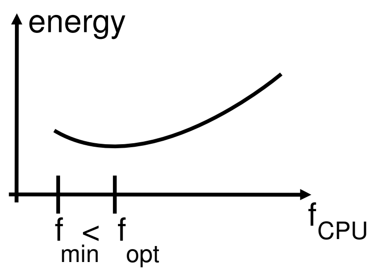
$$C_{bus} = \beta_1 PMC_1 + \beta_2 PMC_2 + \ldots$$

$$C_{cpu} = C_{tot} - C_{mem} - C_{bus} - \ldots$$

Modelling Energy

NICTA





$$E_{tot} = E_{stat} + E_{dyn}$$

$$E_{tot} = P_{stat} T + \int_0^T P_{dyn} dt$$

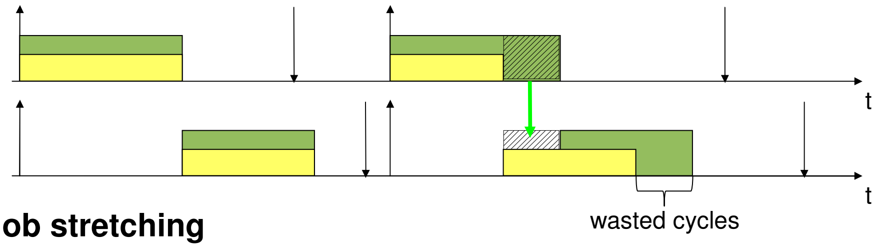
$$\cancel{E_{dyn} \propto fV^2 \Delta t \propto cycles V^2}$$

$$E_{dyn} = V^2 (\chi_{cpu} f_{cpu} + \chi_{bus} f_{bus} + \ldots)\Delta t$$
$$+ \chi_{mem} f_{mem} \Delta t$$
$$+ \gamma_1 PMC_1 + \gamma_2 PMC_2 + \ldots$$
$$+ V^2 (\phi_1 PMC_1 + \phi_2 PMC_2 + \ldots)$$

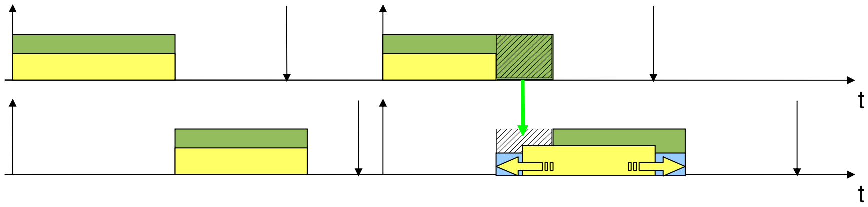
Integration of DVFS

NICTA

Dynamic slack donation



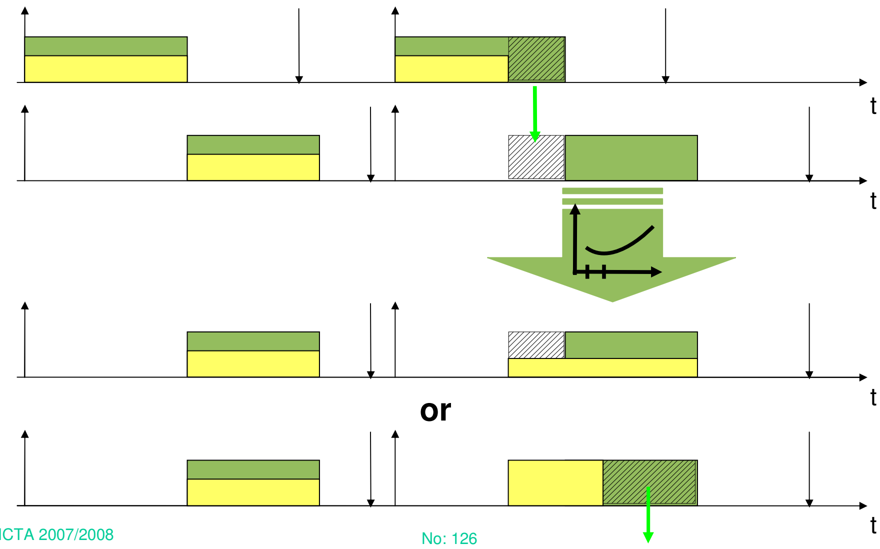
Job stretching



Integration of DVFS: Do we really switch?

NICTA

Job stretching



Algorithm

NICTA

- Switch to another frequency setting if
  - Job can finish on time in the frequency setting (inclusive switching cost)
  - System energy will be minimised

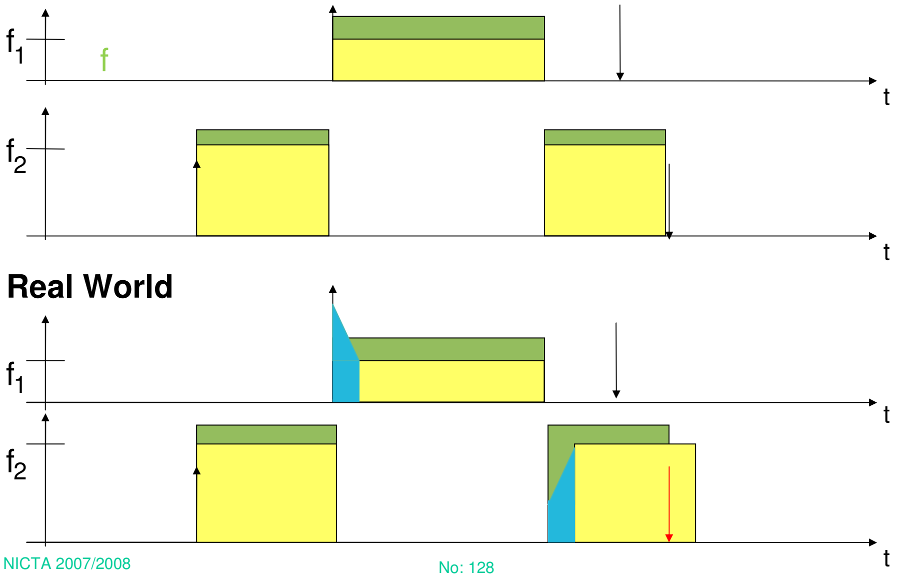
```
newEnergy = energyAtCurrentFrequency
newFrequency = currentFrequency
for frequency in frequencySetPoints
  if WCETAtSwitchedFrequency + switching.WCET < remainingBudet
     && switching.Energy + energyAtSwitchedFrequency < newEnergy
      newEnergy = switchingCost.Energy + energyAtSwitchedFrequency;
      newFrequency = frequency;
if newFrequency != currentFrequency
   switchFrequency (newFrequency);
```


Effects of Switching Times

NICTA

Ideal World

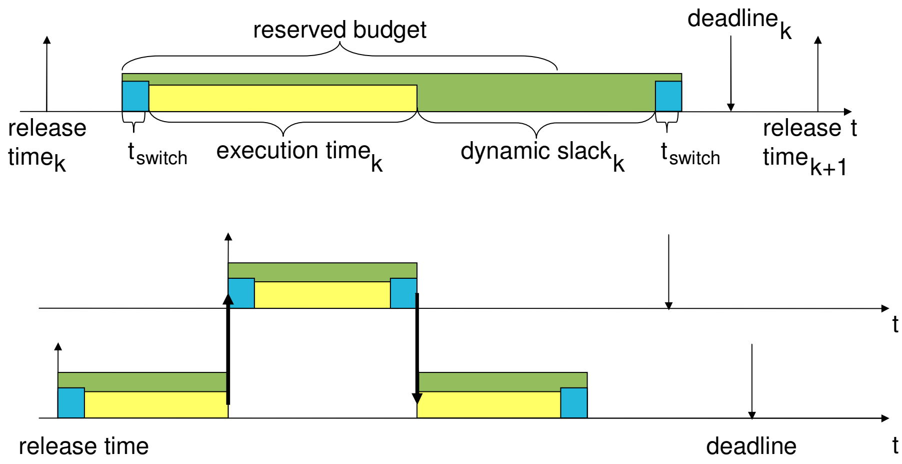
Real World



Switching Time Accounting

NICTA

New task model



Books and other Info

NICTA

Burns, Alan & Wellings, Andrew: Real-Time Systems and Programming Languages (3rd ed), Addison Wesley, 2001

Kopetz, Hermann: Real-time Systems : Design Principles for Distributed Embedded Applications, Kluwer Academic Publishers, 1997

Joseph, Mathai: Real-time Systems: Specification, Verification and Analysis, 2001

http://ebook.ieeelab.com/Embedded/RTSbook.pdf

Dale A. Mackall: *Development and flight test experiences with a flight-crucial digital control system*. NASA Technical Paper 2857, NASA Ames Research Center, Dryden Flight Research Facility, Edwards, CA, 1988.

Basic Priority Ceiling Protocol

- Scheduling:
  - Highest priority task in ready queue gets scheduled. Priority exceptions as below
- Each resource has a ceiling priority equivalent of highest priority using task
- Allocation
  - If resource locked, block
  - If (potentially modified) priority of task higher than the ceiling of any resource not used by that task but used at the time, allocate
  - Else, block
- Priorities:
  - If task τ_1 blocked at resource held by task $\tau_{2:}$
    - τ_2 is lifted in priority to task τ_1
    - revert to original priority once all resources are released

Basic Priority Ceiling and Deadlock

- At any time the priority of task τ_i > ceiling priority of resource currently in use THEN
  1. task τ_l will not require any resource currently in use
  2. Any task τ_k with priority greater than task τ_l will not require any resource currently in use
  - i.e.:
  - No task currently holding a resource can inherit a higher priority and preempt task τ_l w