Suspending Behaviour in Real-Time Embedded Systems

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Outline

- Introduction
- Suspension Models
- Dynamic Suspending Task Model
- Segmented Suspending Task Model
- Conclusion

Optimality of RM/DM and EDF

- For uniprocessor scheduling, if there exists a feasible schedule for ordinary sporadic real-time tasks, scheduling jobs by using EDF is also feasible.
  - EDF scheduling algorithm is optimal

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- RM scheduling algorithm is optimal for fixed-priority scheduling when we consider implicit-deadline (i.e., $T_i = D_i$) ordinary sporadic tasks

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  - EDF scheduling algorithm is optimal
- RM scheduling algorithm is optimal for fixed-priority scheduling when we consider implicit-deadline (i.e., $T_i = D_i$) ordinary sporadic tasks

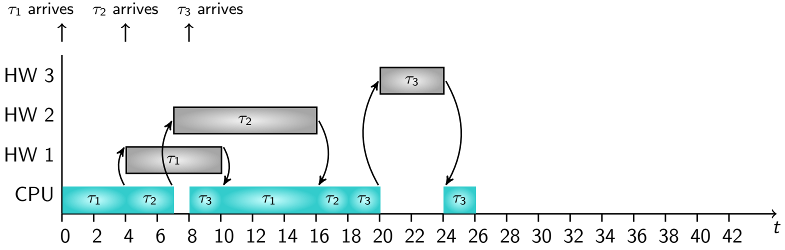
  Time Demand Analysis (TDA): Task τ_k (with $D_i = T_i$) can be feasibly scheduled by a fixed-priority scheduling algorithm if

$$\exists t \text{ with } 0 < t \leq T_k \; \textit{and} \; C_k + \sum_{j=1}^{k-1} \left\lceil \frac{t}{T_j} \right\rceil C_j \leq t.$$

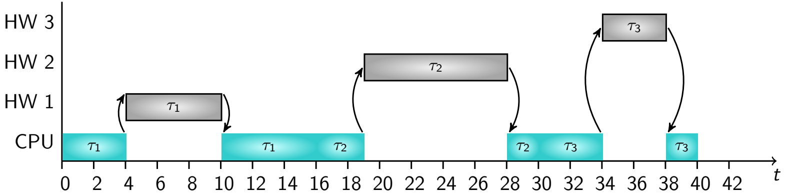
(This talk will implicitly assume $k-1$ higher-priority tasks.)

Reasons for Suspension: Hardware Acceleration

Use FPGA in parallel (suspension aware).



Not use FPGA in parallel (busy waiting).



Reasons for Suspension: Computation Offloading

Pseudo-code for this system

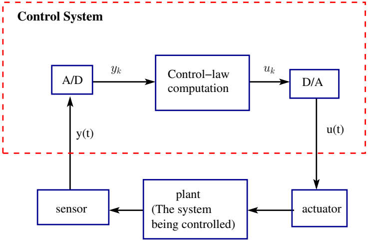
set timer to interrupt periodically with period T;

at each timer interrupt

do

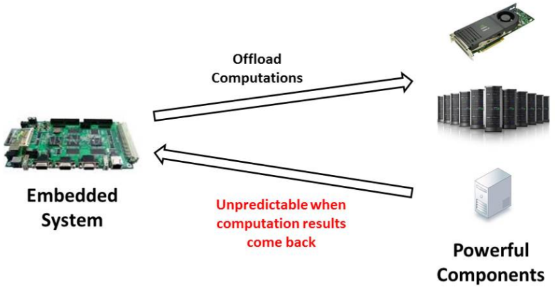
- perform analog-to-digital conversion to get y;
- compute control output u by using external devices;
- output u and do digital-to-analog conversion;

od



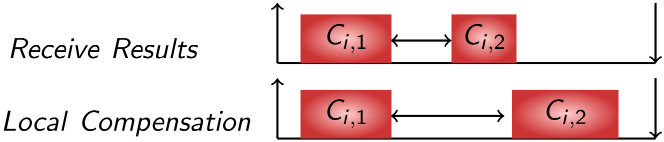
An Example: Unreliable Timing Channels

- Many powerful devices are timing unreliable, which are forbidden in hard real-time systems.
  - Graphics Processing Unit
  - Network Servers
  - Accelerators



Compensation Mechanism

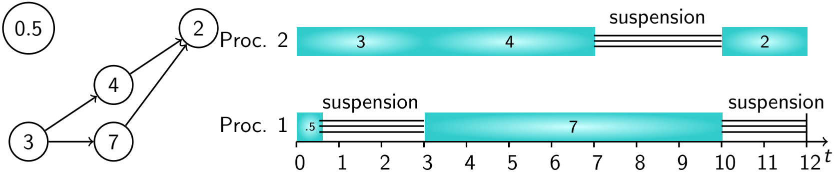
- Based on the timing unpredictable behaviour on many components, we need a local compensation mechanism.



Reasons for Suspension: I/O- or Memory-Intensive

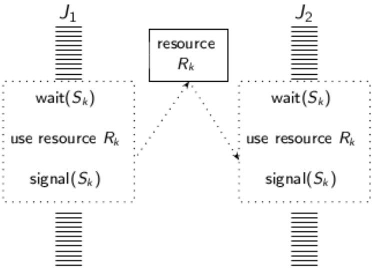
- An I/O-intensive task may have to use DMA to transfer a large amount of data.
- This can take up to a few microseconds to milliseconds.
- Execution pattern of a job is as follows:
  - executes for a certain amount of time,
  - then initiates an I/O activity, and suspends itself.
  - is resumed to the ready queue to be (re)-eligible for execution once the I/O activity completes.
- Such latency can become much more dynamic and larger when we consider multicore platforms with shared memory.

Reasons for Suspension: DAG Structure



- A task may be parallelized such that it can be executed simultaneously on some processors to perform independent computation.
- To this end, we can use a *directed acyclic graph (DAG)* to model the dependency of the subtasks in a sporadic task.
- Each vertex in the DAG represents a subtask

Reasons for Self-Suspensions: Locking Protocols



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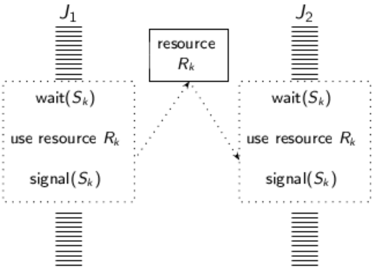
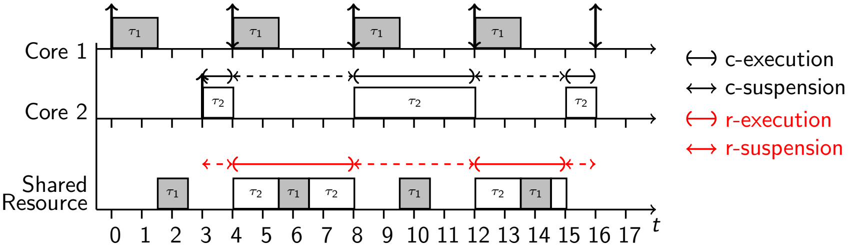


- Semaphores in uniprocessor systems: cause additional blocking due to the mutual exclusion
- Semaphores in multiprocessor systems: cause remote blocking due to the mutual exclusion
  - Suppose that J_1 and J_2 are on two different processors
  - If J_1 locks the semaphore, J_2 has to wait and the processor that runs J_2 may have to idle.

Reasons for Self-Suspensions: Physical Resource Sharing

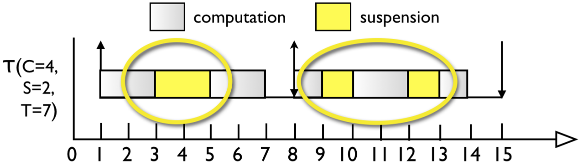


- Multiple cores may share a bus
- The contention on the bus can be considered as a suspension problem (with respect to the bus access)

Outline

Possible Self Suspensions

Implicit-deadline sporadic suspending task: $\tau(C, S, T)$



Jobs may alternate between computation and suspension phases without any restriction on how they interleave

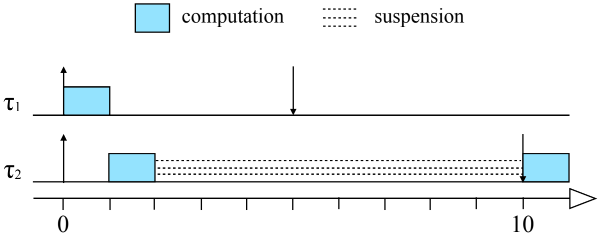
- 1-Segmented self-suspension: 2 computation segments separated by a suspension interval
- Segmented self-suspension: f computation segments separated by $f - 1$ suspension intervals
- Dynamic self-suspension: the suspension pattern is unknown and can be arbitrary

Terminologies

- $C_{i,j}$ or C_i^j: the worst-case execution time for task τ_i in the j-th computation segment
- C_i: the worst-case execution time for task τ_i
- $S_{i,j}$ or S_i^j: the self-suspension time for task τ_i in the j-th suspension interval
- S_i: the self-suspension time for task τ_i
- T_i: period of task τ_i
- D_i: relative deadline of task τ_i. I will implicitly assume $T_i = D_i$, unless it is specified.
- U_i: utilization of task τ_i, defined as $\frac{C_i}{T_i}$

Counterexample for RM and EDF

- $C_1 = 1,\ S_1 = 0,\ D_1 = 5,\ T_1 = \infty.$
- $C_{2,1} = 1,\ S_2 = 8,\ C_{2,2} = 1,\ D_2 = 10,\ T_2 = 10.$



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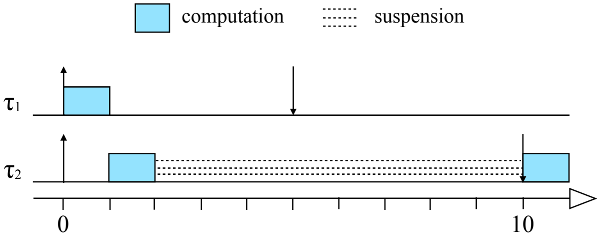

- We can easily extend to let S_2 to be very large.
- EDF and Rate-Monotonic are in general not good.

Wait, What does this Mean?

- The gain by offloading can be completely useless
- The remote blocking and synchronization can completely destroy the feasibility
- Existing scheduling algorithms are not going to work very well
- Suspension has triggered a new dimension for designing systems
- If suspension is not handled carefully, the suspension may be harmful to the system utilization

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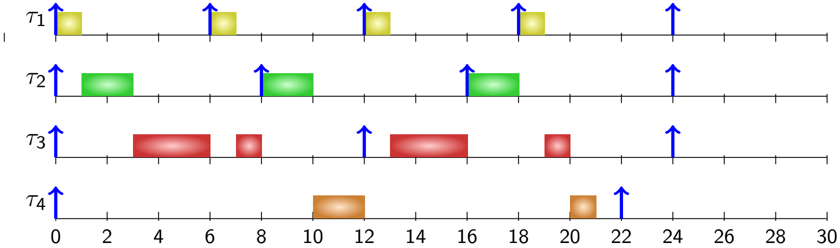
- Existing scheduling algorithms are not going to work very well
- Suspension has triggered a new dimension for designing systems
- If suspension is not handled carefully, the suspension may be harmful to the system utilization
- So, the key is to utilize and analyze the suspension impact well.

Outline

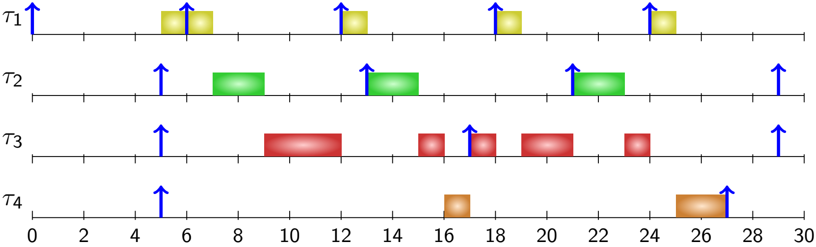
The Golden Critical Instant Theorem for FP Scheduling



- Release the higher-priority tasks at the same time as the task (here τ_k) under analysis
- The following jobs of a higher-priority task should be released then by following the period constraint

$$\exists t \text{ with } 0 < t \leq T_k \;\; and \;\; C_k + \sum_{j=1}^{k-1} \left\lceil \frac{t}{T_j} \right\rceil C_j \leq t.$$

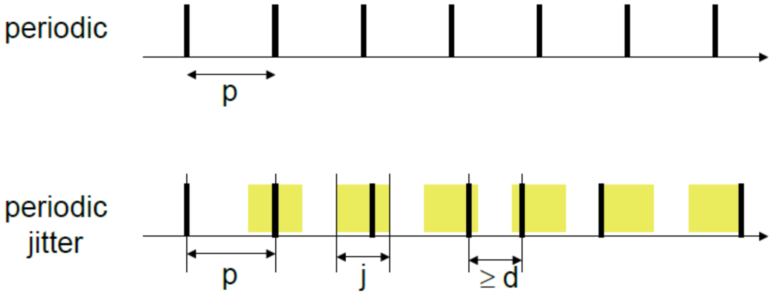
Suspension Induces Jitter



- The response time of task τ_4 becomes $27 - 5 = 22$. (It was 21 if there is no suspension.)
- Is this the worst case if only task τ_1 suspends itself?

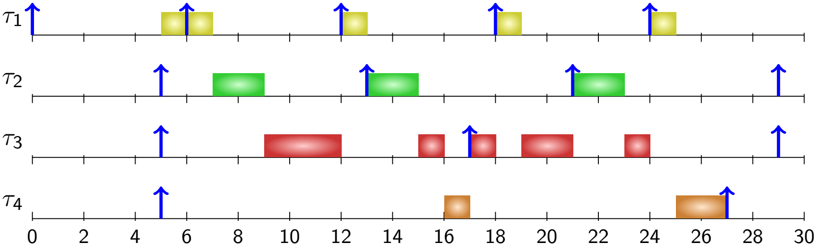
Periodic Tasks with Jitter (pjd Tasks)

A common event pattern (that is not purely periodic) can be specified by the parameter triple (p, j, d), where p denotes the period, j the jitter, and d the minimum inter-arrival distance of events in the modeled stream.



courtesy slide from Lothar Thiele.

Suspension Creates Jitter (cont.)



- A self-suspending task τ_i is a PJD task
  - Period is T_i
  - Jitter is S_i
  - Minimum inter-arrival time is C_i (I will not use this constraint.)

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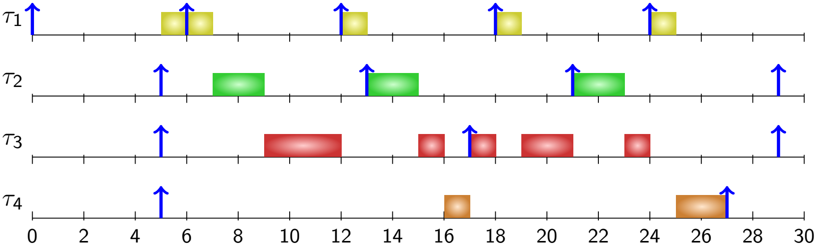


- A self-suspending task τ_i is a PJD task
  - Period is T_i
  - Jitter is S_i
  - Minimum inter-arrival time is C_i (I will not use this constraint.)
- Schedulability test of task τ_k:

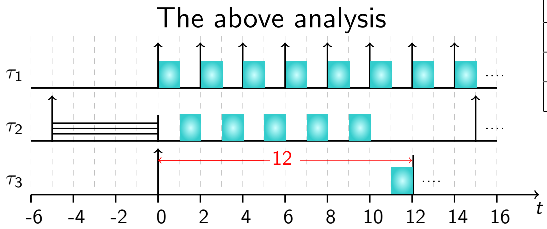
$$\exists t \text{ with } 0 < t \leq T_k \;\; and \;\; C_k + S_k + \sum_{j=1}^{k-1} \left\lceil \frac{t + S_j}{T_j} \right\rceil C_j \leq t.$$

Suspension-Aware Schedulability Analysis

The following papers are based on this observation

- Meng, RTCSA 1994
- Kim et al., RTCSA 1995
- Audsley and Bletsas, ECRTS 2004
- Audsley and Bletsas, RTAS 2004
- Lakshmannan and Rajkumar, RTSS 2009 for multiprocessor synhchronization problems
- Several other papers (10+) that are based on Lakshmannan and Rajkumar in RTSS 2009.

An Example



τ_i	C_i	S_i	T_i
τ_1	1	0	2
τ_2	5	5	20
τ_3	1	0	∞

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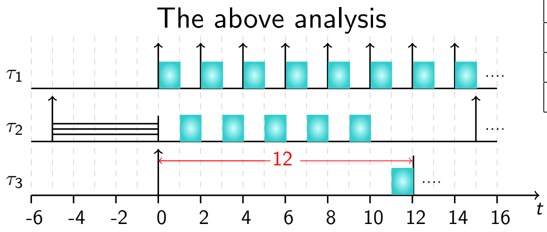

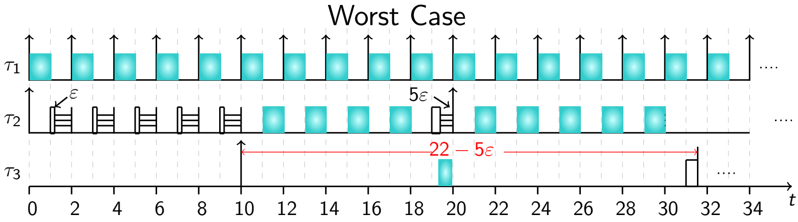

What was the Misconception?

The above analysis is incorrect.

Too optimistic!

- The setting of jitter to S_i is too *optimistic*.
- The impact: the following papers are based on this observation
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  - Kim et al., RTCSA 1995 (flawed)
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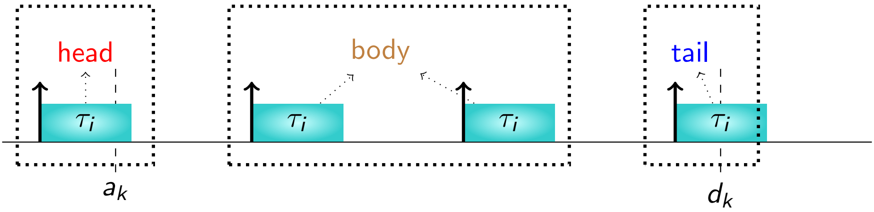
How to Fix It? Be Pessimistic!



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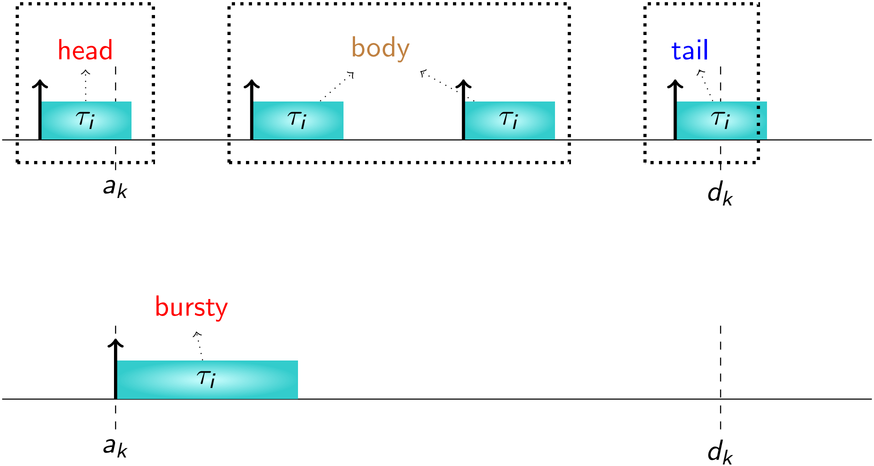

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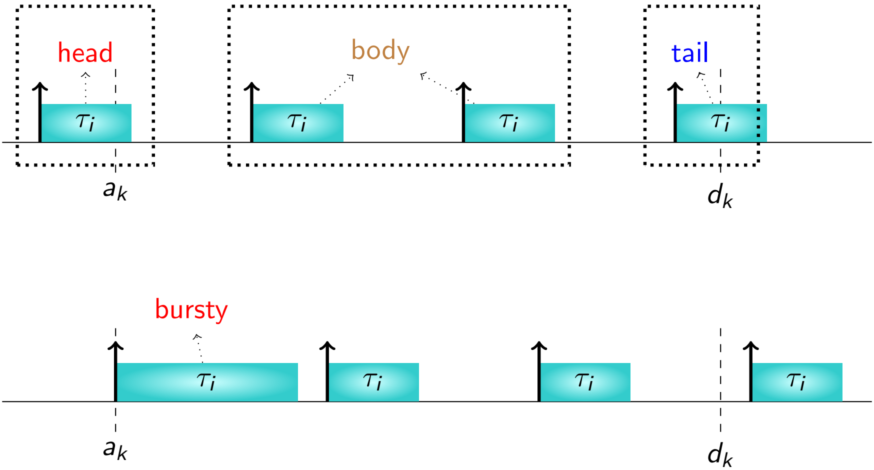

Time-Demand Schedulability Analysis

Task τ_k is schedulable under fixed-priority scheduling in a self-suspension task set, if

$$\exists t \text{ with } 0 < t \leq T_k \;\; and \;\; C_k + S_k + \sum_{i=1}^{k-1} W_i(t) \leq t,$$

where

$$W_i(t) = \left(\left\lceil \frac{t}{T_i} \right\rceil - 1 \right) C_i + 2C_i.$$

Or, equivalently, the jitter of a higher-priority task τ_i is T_i.

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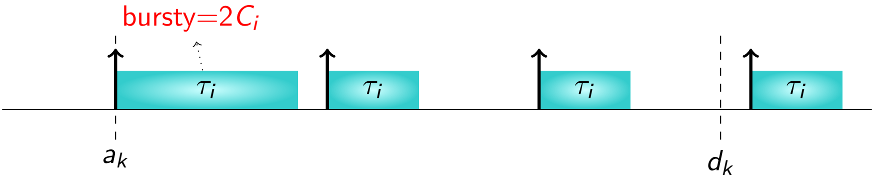

Utilization-Based Analysis

Theorem (Bini et al. in ECRTS 2001)

Any sporadic task set is schedulable under RM if the following conditions hold:

$$\forall 1 \leq k \leq n, \boxed{U_k} \leq 1 - (\boxed{1} + 1) \cdot \left(1 - \frac{1}{\prod_{i=1}^{k-1}(U_i + 1)}\right). \quad (1)$$

Theorem (Liu and Layland JACM 1973)

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Utilization-Based Analysis

Theorem (Liu and Chen in RTSS 2014)

Any sporadic $\boxed{self - suspending}$ *task set is schedulable under RM if the following conditions hold:*

$$\forall 1 \leq k \leq n, \boxed{U_k + \frac{S_k}{T_k}} \leq 1 - (\boxed{2} + 1) \cdot \left(1 - \frac{1}{\prod_{i=1}^{k-1}(U_i + 1)}\right). \quad (1)$$

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Calculating Suspension Time Can Be Also Tricky

- The original analysis in distributed priority ceiling protocol (DPCP by Rajkumar in ICDCS 1990)
  - Non-nested critical sections
  - Critical sections guarded by one semaphore are always executed on one dedicated processor
  - Three tasks, each of them assigned on one processor, using one binary semaphore on $Proc_0$.

τ_i	$Proc(\tau_i)$	C_i	T_i $(= D_i)$	N_k	L_i
τ_1	$Proc_1$	6	10	1	2
τ_2	$Proc_2$	11	18	1	4
τ_3	$Proc_3$	8	20	3	1

  - C_i: worst-case execution time (including the critical section length)
  - T_i: the period
  - N_i: the number of critical sections per job invocation
  - L_i: the worst-case critical section length (per critical section).

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- Multi-tasking only takes place on $Proc_0$
- The original analysis argues that the additional delay B_k due to DPCP on $Proc_0$ for task τ_k is upper bounded by $\mathrm{B}_k \leq N_k \cdot (\max_{j>k} \mathrm{L}_j) + \sum_{i=1}^{k-1} \left\lceil \frac{T_k}{T_i} \right\rceil L_i\ \mathrm{N}_i$.
  - The first term is due to the fact that each critical section access can be blocked by a lower-priority task.
  - The second term is due to the interference from the higher-priority tasks under the critical instant theorem.

  Therefore,
  - B_1 is upper bounded by 4,
  - B_2 is upper bounded by $1 + 2 \cdot 2 = 5$, and
  - B_3 is upper bounded by $0 + 2 \cdot 2 + 4 \cdot 2 = 12$.

Something Went Wrong

τ_i	$Proc(\tau_i)$	C_i	$T_i\ (= D_i)$	N_k	L_i
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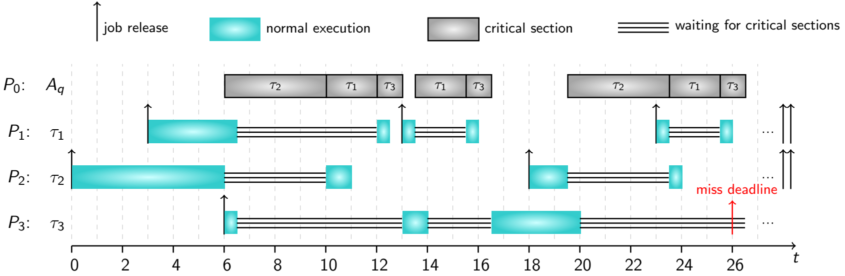

A job of task τ_3: run 0.5 time unit on $Proc_3$, critical section 1 time unit, run 1 time unit on $Proc_3$, access the critical section for 1 time unit, run 3.5 time units on $Proc_3$, and access the critical section for 1 time unit

Impact

- This wrong quantification of suspension time was used by
  - R. Rajkumar, L. Sha, and J. Lehoczky, in RTSS 1988.
  - R. Rajkumar, in ICDCS 1990.
  - B. Victor and G. Kang, IEEE Transactions on Software Engineering, vol. 21, no. 10, pp. 834-844, 1995.
  - Lakshmannan and Rajkumar, RTSS 2009
  - P. Hsiu, D. Lee, and T. Kuo, in EMSOFT 2011.
  - F. Nemati, M. Behnam, and T. Nolte, in ECRTS 2011.
- Correct settings of jitter can solve this problem

Can We Do Better? Suspension as Blocking

- In the textbook "Real-Time Systems" by Jane W. S. Liu, she proposed to model the *extra delay* as blocking denoted as B_k:
  - The blocking time contributed from task τ_k is S_k.
  - A higher-priority task τ_i can only block the execution of task τ_k by at most $min(C_i, S_i)$.

$$B_k = S_k + \sum_{i=1}^{k-1} min(C_i, S_i).$$

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If the argument is correct, we can revise the analysis:

$$\exists t \mid 0 < t \leq T_k, \qquad C_k + B_k + \sum_{i=1}^{k-1} \left\lceil \frac{t}{T_i} \right\rceil C_i \leq t.$$

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This was also used by Rajkumar et al. in RTSS 1988 and ICDCS 1990.

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The analysis is correct!

Jian-Jia Chen, Geoffrey Nelissen and Wen-Hung Huang, "A Unifying Response Time Analysis Framework for Dynamic Self-Suspending Tasks", in ECRTS 2016.

Outline

Segmented Suspension

- Arbitrary suspension model provides an easy way to specify suspending systems
  - suffers from the poor schedulability
  - using arbitrary suspension blindly is too pessimistic
- When the suspension patterns are known (or are specified with certain guarantees), it is better to use segmented suspensions.

Period Enforcer

- Rajkumar in 1991 proposed the *period enforcer* algorithm
- It is a technique to control the processor demand.
- The key idea: artificially delay the execution of computation segments if a job resumes *too soon*.
- The period enforcer algorithm determines for each computation segment an *eligibility time*.
- If a segment resumes before its eligibility time, the execution of the segment is delayed until the eligibility time is reached.

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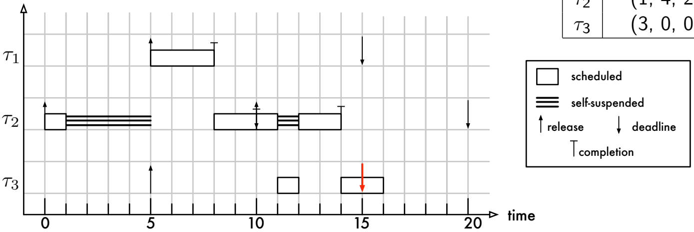
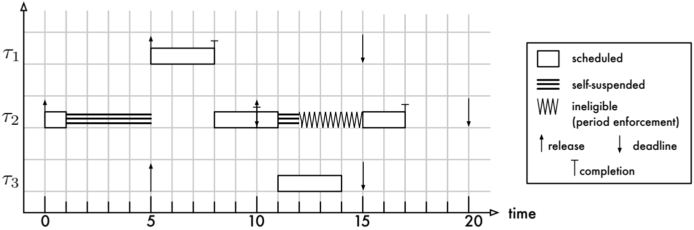
- It is a technique to control the processor demand.
- The key idea: artificially delay the execution of computation segments if a job resumes *too soon*.
- The period enforcer algorithm determines for each computation segment an *eligibility time*.
- If a segment resumes before its eligibility time, the execution of the segment is delayed until the eligibility time is reached.
- You can imagine that this is like a sporadic server.

Period Enforcer: An Example

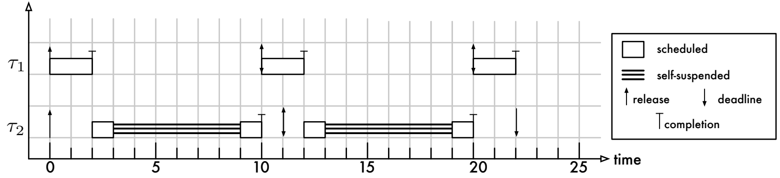
	(C_i^1, S_i^1, C_i^2)	$D_i = T_i$
τ_1	(3, 0, 0)	10
τ_2	(1, 4, 2)	10
τ_3	(3, 0, 0)	10

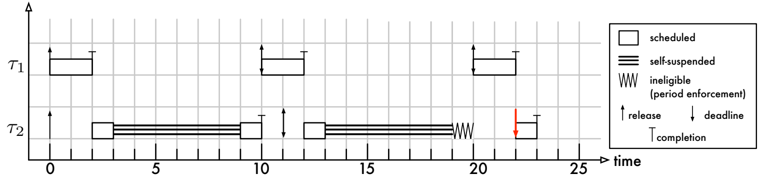




Period Enforcement Can Induce Deadline Misses

	(C_i^1, S_i^1, C_i^2)	$D_i = T_i$
τ_1	(2, 0, 0)	10
τ_2	(1, 6, 1)	11





Critical Instant?

Let's consider the simplest case under fixed-priority scheduling:

- τ_k is the lowest priority task
- all the higher priority tasks are sporadic and non-self-suspending

Lakshmanan and Rajkumar (in RTAS 2010) proved that the critical instant of task τ_k is as follows:

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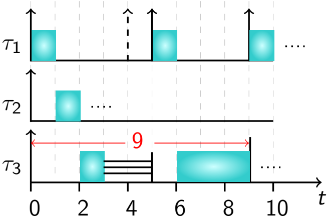
- every task releases a job simultaneously with τ_k;
- the jobs of higher priority tasks that are eligible to be released during the self-suspension interval of τ_k are delayed to be aligned with the release of the subsequent computation segment of τ_k; and
- all the remaining jobs of the higher priority tasks are released with their minimum inter-arrival time.

An Example

	(C_i^1, S_i^1, C_i^2)	$D_i = T_i$
τ_1	(1, 0, 0)	4
τ_2	(1, 0, 0)	9
τ_3	(1, 2, 3)	9



(a) Lakshmannan's Critical Instant.

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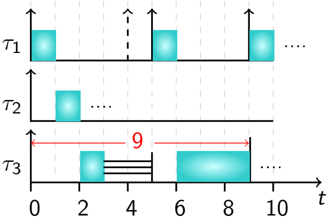

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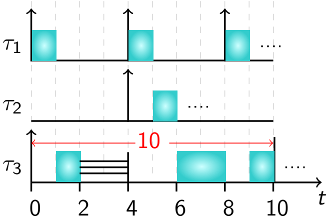
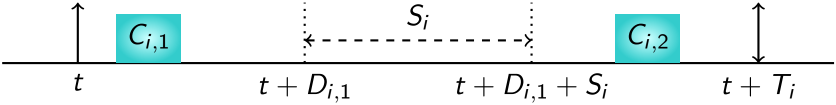


(b) Do not release jobs synchronously.

Counterexample provided by Nelissen et al. in ECRTS 2015.

Fixed-Relative-Deadline (FRD) Approaches



- When a job of task τ_i arrives at time t,
  - the absolute deadline of the job in the first computation phase is set to $t + D_{i,1}$
  - the suspension has to be finished before $t + D_{i,1} + S_i$,
  - the release time of the second subjob (the second computation phase) is $t + D_{i,1} + S_i$
  - the absolute deadline of the second subjob is $t + T_i$

Proportional Fixed-Relative Deadline Assignments

Liu et al. in DAC 2014 for only one suspension interval per task.

- $D_{i,1} = \frac{C_{i,1}}{C_{i,1}+C_{i,2}}(T_i - S_i)$
- $D_{i,2} = \frac{C_{i,2}}{C_{i,1}+C_{i,2}}(T_i - S_i)$
- Therefore, we have $\frac{C_{i,1}}{D_{i,1}} = \frac{C_{i,2}}{D_{i,2}} = \frac{C_{i,1}+C_{i,2}}{T_i-S_i}$
- Is Proportional FRD Good?
  - It can be proved that this does not yield good analytical bounds.

Equal-Deadline Assignment (EDA)

Chen and Liu in RTSS 2014

$$D_{i,1} = D_{i,2} = \frac{T_i - S_i}{2}.$$

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Remarks

Huang and Chen (DATE 2016): extended to fixed-priority scheduling and multiple suspension intervals.

Different Priority per Computation Segment

	$(C_{i,1}, S_{i,1}, C_{i,2}$	$D_i = T_i$
τ_1	$(10, 0, 0)$	30
τ_2	$(5, 5, 16)$	40

- Priority level: $C_2^1 - C_1^1 - C_2^2$
  - One may conclude that the worst-case response time of C_2^1 is 5 and the worst-case response time of C_2^2 is $16 + 10 = 26$.
  - Since $5 + 5 + 26 = 36 \leq 40$, the lowest-priority segment can meet the deadline.

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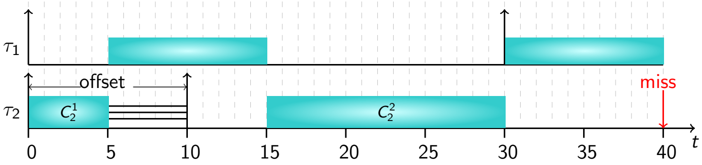

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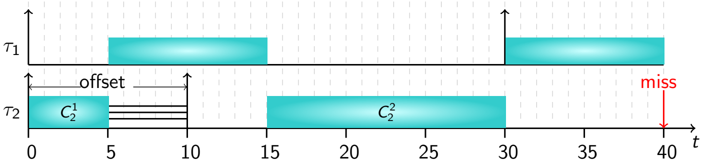

- Yes, possible, but pay attention
  - This was used by Kim et al. RTSS 2013, and Ding et al. in IEICE Transactions 2009.

Outline

Conclusion

- Suspension can be very harmful if it is not treated well
- Suspension relates to important features in the era of multicore systems and cyber-physical systems
  - Computation offloading
  - Shared memory and bus in multicore systems
  - Virtual shared resources (like semaphores) in multicore systems
  - GPU/FPGA acceleration
  - etc.
- This is a non-trivial problem
  - Studied already early in 90's but with quite a few misconceptions
  - Broken literature

Positive Results

- Wen-Hung Huang and Jian-Jia Chen. Schedulability and Priority Assignment for Multi-Segment Self-Suspending Real-Time Tasks under Fixed-Priority Scheduling. *under preparation*.
- Wen-Hung Huang and Jian-Jia Chen. Self-Suspension Real-Time Tasks under Fixed-Relative-Deadline Fixed-Priority Scheduling. in DATE, 2016
- Wen-Hung Huang, Jian-Jia Chen, Husheng Zhou and Cong Liu. PASS: Priority Assignment of Real-Time Tasks with Dynamic Suspending Behavior under Fixed-Priority Scheduling, in DAC, 2015.
- Jian-Jia Chen, Cong Liu: Fixed-Relative-Deadline Scheduling of Hard Real-Time Tasks with Self-Suspensions. in RTSS 2014
- Cong Liu, Jian-Jia Chen: Bursty-Interference Analysis Techniques for Analyzing Complex Real-Time Task Models. in RTSS 2014
- Wei Liu, Jian-Jia Chen, Anas Toma, Tei-Wei Kuo, Qingxu Deng: Computation Offloading by Using Timing Unreliable Components in Real-Time Systems. in DAC 2014