Task Synchronization on Multiprocessors

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Lecture #18

Multiprocessor Task Synchronization

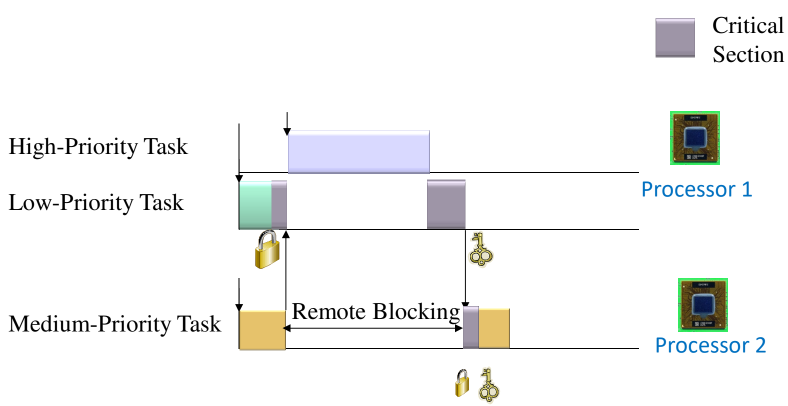
- Multiprocessor synchronization challenges
  - Remote blocking
  - Self-suspending behavior
  - Multiple priority inversions due to suspensions
- Uniprocessor solutions need to be revisited
  - Priority inheritance protocols
  - Priority ceiling protocol

Revisiting Blocking from Resource Sharing

- Consider the blocking term B_i of a task τ_i as the **additional time penalty** incurred by τ_i due to resource sharing **relative to the case when there is absolutely *no* resource sharing** in the taskset.
- On a uniprocessor, when one of the priority inheritance protocols is used, only the critical sections of lower priority tasks can contribute to B_i
  - Under the **basic priority inheritance protocol**, up to *(m, n)* critical sections of lower priority critical sections, where *n* is the number of tasks with lower priority than τ_i and *m* is the number of mutexes accessed by lower-priority tasks with a priority ceiling higher than or equal to the priority of τ_i
  - Under the **priority ceiling protocol**, at most one critical section of a lower-priority task with a priority ceiling higher than or equal to the priority of τ_i
  - The **highest locker protocol** has the same property as the priority ceiling protocol
  - Under the **non-preemption protocol**, at most any critical section of a lower-priority task

Remote Blocking

- Remote Blocking
  - Tasks wait on resources held on other cores
  - Leads to wastage of CPU utilization

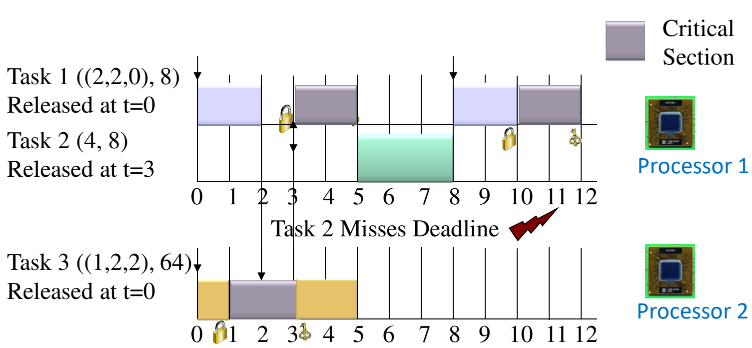


Multiprocessor Resource Sharing

- If a task shares a resource with a task on any other (remote) processor, it may pay an additional penalty.
- So, sharing resources with tasks of **any** priority on **any** other processor can contribute to an increase in B_i.

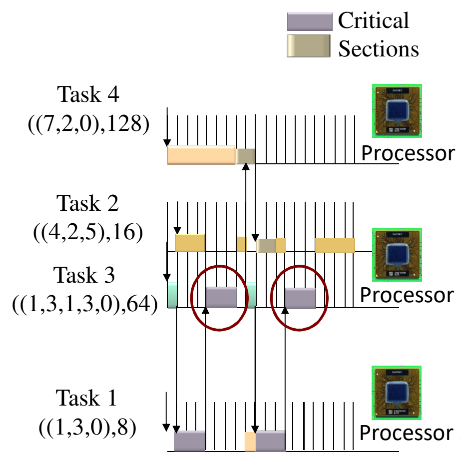
Self-Suspending Tasks

- Tasks suspend on remote cores
  - In the uni-processor context
    - Tasks suspend on other tasks in the same processor
  - Leads to various scheduling penalties



Multiple Priority Inversions

- When a task suspends
  - Lower-priority tasks could be released
  - Lower-priority tasks could acquire resources
    - Due to priority ceiling, they can cause preemptions
- The worst case:
  - For each task segment,
  - One preemption from each lower-priority task



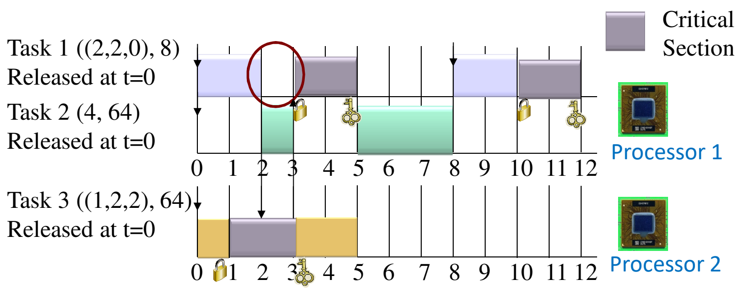
Priority Ceiling Protocol Extension

- Multiprocessor Priority Ceiling Protocol (MPCP)
  - **Global critical sections** guarded by **global mutexes**
  - Global mutexes associated with global priorities
    - **(Global) Priority ceiling of global mutex G_M** is calculated as:

      Max (All task normal execution priorities) +
      1 + Max (Normal priorities of tasks accessing G_M)
- Critical section executions can be preempted
  - By other critical section executions with an even greater priority ceiling
- Each mutex M_G has a priority queue
  - Pending tasks acquire mutex in priority order

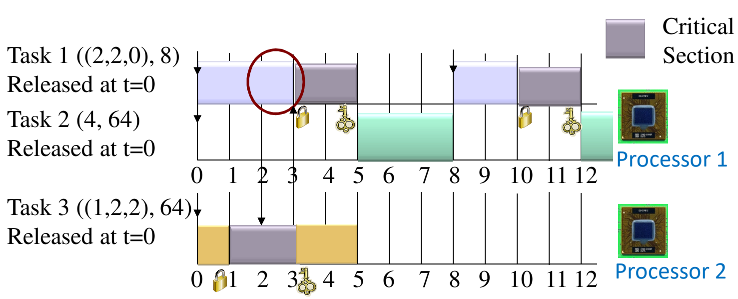
Suspension-based Protocol

- When global mutex request is pending
  - Task suspended and other active tasks execute
- Issues:
  - Self-suspension, multiple priority inversions



Spinning-based Protocol

- When a global mutex request is pending
  - Task continues to “spin” till it acquires resource
- Issues:
  - Spinning-based utilization loss



Evaluating The Effectiveness of Bin-Packing

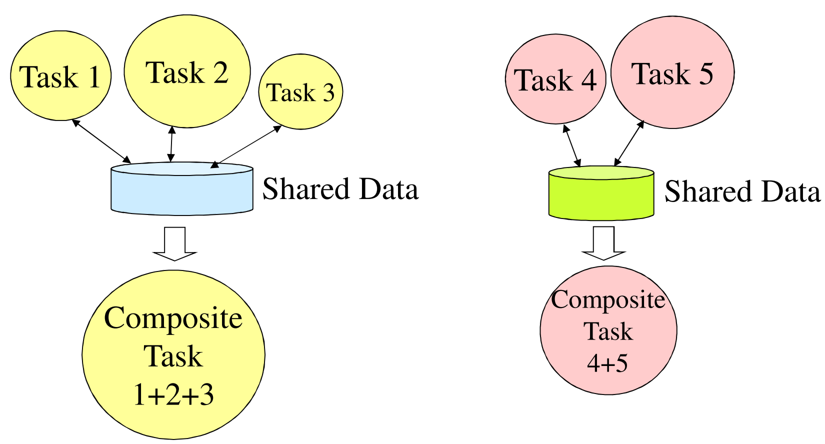
- Suppose the number of bins required by scheme *S* to pack a set of objects is $|S|$.
- One may want to compare the performance of a bin-packing heuristic *H* with that of the *optimal* scheme *O*
- Analyses:
  - **Worst-case analysis**: theoretical study to determine the absolute worst-case number of bins required by *H* relative to that of *O*
    - i.e. find $max(|H| \div |O|)$
  - **Average-case analysis**: compute $(|H| \div |O|)$ for randomly picked sets of objects
    - Perform over a large sample so that results are statistically significant
    - How do we know $|O|$?
      - Finding the optimal packing is NP-hard:
      - Will take an exponential amount of time (unless P = NP)
    - Create by construction!
      - Assume fully packed bins: split into known # of objects in each bin into random sizes (for a given # of bins = |O|)
      - Unpack these objects and offer to heuristic for packing
      - Original packing we started with is optimal!

Synchronization-Aware Bin-Packing

Making Bin-Packing Synchronization-Aware

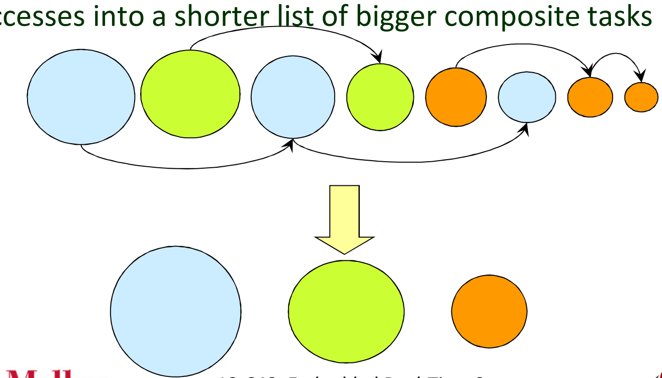
- Global critical sections lead to
  - Significantly more blocking (i.e. the B_i term becomes much bigger)
    - "Blocking" can be caused both by-higher priority and lower-priority tasks on other processors.
  - Deferred execution behaviors can result in scheduling penalties
- Conversely, local critical sections
  - Utilize the (local) priority ceiling protocols (like the highest locker priority) to bound B_i to a single (local) critical section of a lower priority task
  - Experience no deferred execution penalties
- Our bin-packing heuristics use object size as the primary criterion while packing objects into bins
- Can we try to exploit the bin-packing heuristics and try to make "global critical sections" become local ones?
  - Combine objects (tasks) into **composite objects**.

Synchronization-Aware Packing



Bin-Packing → Packing of Composite Objects

- If tasks A and B share data, they become a composite task
  - Applies recursively: task A and/or B can also be a composite task
  - The relationship is transitive:
    - i.e. if tasks A and B share one piece of data, and tasks B and C share another piece of data, tasks A, B and C become a single composite task
- Transform the given list of tasks with their shared resource accesses into a shorter list of bigger composite tasks



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Bin-Packing of Composite Objects

- Use bin-packing heuristics to allocate composite tasks to bins
  1. If a composite task does not fit into a bin, set it aside and allocate other unallocated tasks
  2. After current iteration of allocation, if any unallocated tasks remain, then try to allocate them
     - This reduces the number of global critical sections
  3. If a composite task does not fit any bin, split into two objects with *minimum synchronization cost* and allocate. If a task cannot be split (i.e. it is an *elementary* task and not a *composite* task), you must create a new bin.
  4. Go to Step 1.

Other variations are possible.

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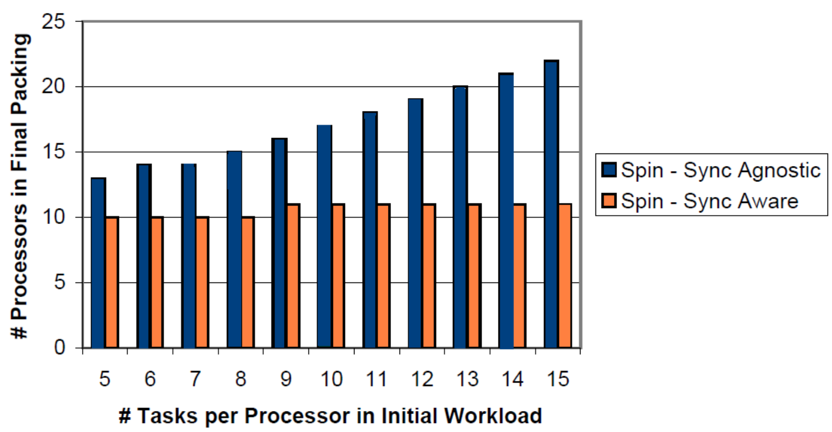
Comparison of Schemes

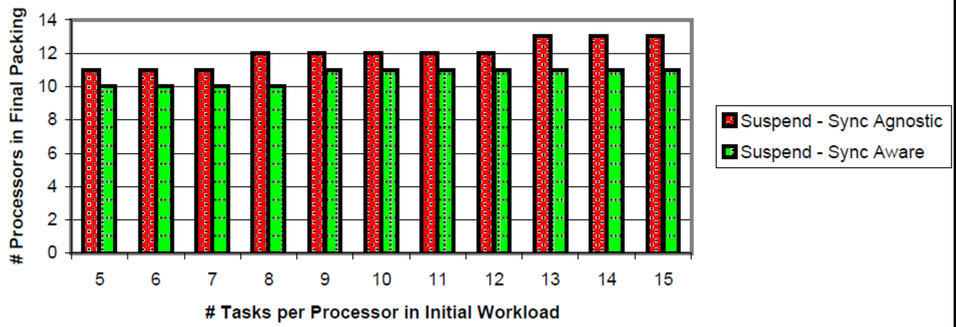
- Synchronization itself between the objects <u>after</u> allocation can be either spin-based or suspension-based.
- Evaluation is <u>*very*</u> dependent on assumptions:
  - Distribution of task utilization (object sizes)
  - Amount of sharing (# of tasks that share the same resources)
  - Number of resource accesses per task
  - Length of each critical section
  - Overhead of preemptions
  - Overhead of caching penalty during preemptions

Synchronization-Aware Bin Packing - Spinning



8 fully packed cores, 2 critical sections per task, 2 lockers per mutex
500µs critical sections, Periods: [10ms, 100ms]

Synchronization-Aware Bin Packing - Suspension

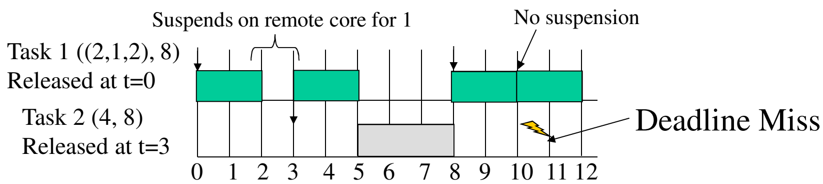


8 fully packed cores, 2 critical sections per task, 2 lockers per mutex
500µs critical sections, Periods: [10ms, 100ms]

Dealing with Deferred Execution

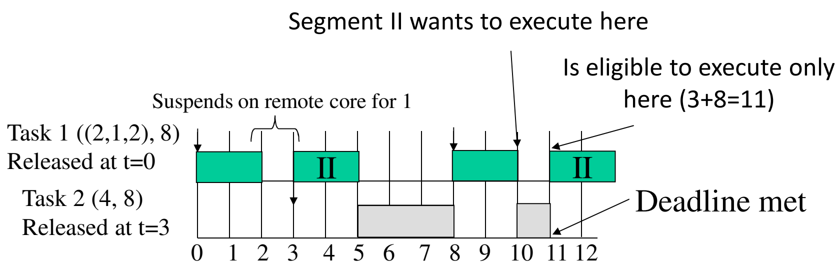
Self-Suspending Tasks

- Tasks can suspend due to variety of reasons:
  - Sensor Input
  - Synchronization with other processing core
  - Waiting on co-processor
- Consider the example:
  - Task 1: Period 8: Executes for 2 units, Suspends for at most 1 unit, Continues execution for 2 more units
  - Task 2: Period 8: Execution for 4 units



Solution: Period Enforcement

- An execution segment becomes eligible to execute only at periodic boundaries.
- If a task suspends itself during execution (for any reason including suspension on a shared resource that is locked by a task on a remote processor), execution before and after suspension is each considered an execution segment.



Conclusions

- Both bin-packing and partitioned scheduling can be improved by “splitting” tasks
  - At most one task needs to be split per processor
- Period transformation can be used to reconcile scheduling priority and semantic importance of tasks
- With harmonic tasks and splitting, we can get 100% schedulable utilization per processor
- Multiprocessor synchronization schemes
  - Period enforcement
  - Static and dynamic slack enforcement