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HYPERVERSOR DETERMINISM ON MODERN SOC

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INTRODUCTION
WHY HYPERVISORS IN EMBEDDED SYSTEMS

▶ Origin: Server consolidation → also useful for complex embedded systems for:
  ▶ Safety:
    ▶ Mixed criticality systems
    ▶ Software redundancy (e.g. multi version dissimilar code)
    ▶ Online monitoring (e.g. for graceful degradation)

  ▶ Security:
    ▶ MILS Systems
    ▶ Online monitoring (e.g. for intrusion detection)

  ▶ Efficiency: Improve resource utilization
  ▶ Combine different levels of real-time requirements
  ▶ (Legal reasons: License isolation)
A HYPERVISOR PROVIDES ...

- ... multiple instances of the underlying physical machine
- ... each with its own subset of system resources (→ isolated and independent)
- ... each can run its own specialised OS w/ apps
- Sole mandatory trusted code for all: the hypervisor
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HYPERVISOR: DEFINITION

From Wikipedia, paraphrasing [PG74]:
“A virtual machine monitor (VMM, also called hypervisor) is the piece of software that provides the abstraction of a virtual machine. There are three properties of interest when analyzing the environment created by a VMM:“

- Equivalence / Fidelity:
  “A program running under the VMM should exhibit a behavior essentially identical to that demonstrated when running on an equivalent machine directly."

- Resource control / Safety:
  “The VMM must be in complete control of the virtualized resources."

- Efficiency / Performance:
  “A statistically dominant fraction of machine instructions must be executed without VMM intervention."

“ESSENTIALLY IDENTICAL“ ... 

▶ “Any program run under the hypervisor should exhibit an effect identical with that demonstrated if the program had been run on the original machine directly, with the possible exception of differences caused by the availability of system resources and differences caused by timing dependencies.“

⇒ Determinism is normally not within the scope of Hypervisors.
⇒ **Scope of Hypervisors must be extended.**
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REQUIREMENTS AND NON-REQUIREMENTS
FEATURES WE WANT

- Safe isolation between VMs
  - Achieved by resource partitioning

- Interaction between VMs
  - Any interaction must be under hypervisor’s control

- Temporal determinism
  - Requires extension (see above) → subject of this talk
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FEATURES WE MAY NOT NEED

- Virtual memory
  - Two aspects: virtual addressing and protection
  - For partitioning: just having protection suffices
  - Some low end SoCs lack mapping capability (only MPU)

- Dynamic reconfiguration
  - I.e. changing a VM’s allocated resources at run-time
  - Live migration
    - Significant complexity in HV and VM
  - Needed (if at all) only by best effort (non-realtime)VMs

- “Standard“ ABI compatibility
  - e.g. IA32 / 64 / Windows
  - Often irrelevant for SoCs
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HYPERVERSION BASICS
HYPervisor Basics: Architectural Classification

- Type 1: Run on bare metal
- Classical: Hardware assisted, full virtualization architecture must be "virtualisable" (according to [PG74])
- Paravirtualisation & microkernels
  Privileged software (kernel) needs to be adapted
- Binary rewriting, aka "just in time paravirtualisation":
  Full virtualisation for non-virtualisable architectures
- Special cases
  e.g. leveraging ARM TrustZone

```
+---+     +---+     +---+
| VM #1 |     | VM #2 |     | VM #3 |
| App | App | App | App | App |
| Guest OS |     | Guest OS |     | Guest OS |
| Hypervisor |     | Hardware (SoC) |
```
HYPERVISOR BASICS: ARCHITECTURAL CLASSIFICATION

- Type 2: Run on another OS
  - One more layer in scheduler hierarchy → needs to be controlled for determinism
  - Benefits for embedded systems are questionable (See “Standard“ ABI compatibility)
Microkernels: Different origin ...

- Minimise privileged (e.g. kernel) code
- Separate policy from mechanism
- IPC as central (only) service

... but similar results

- E.g. the Lites Server [Hel94] and L4Linux [HHL\textsuperscript{+}97] were paravirtualised UNIX kernels

- Generally more flexible

- No significant differences wrt. scheduling / determinism (however: ongoing attempts to push scheduling policy out of the kernel [GGB\textsuperscript{+}17])
MICROKERNELS VS. HYPERVERVISORS

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HYPERVERSOR CPU ALLOCATION

1. Static allocation of CPUs to VMs
   - Hardware as well as software solutions exist

- No\(^1\) or very little software required
- No Very little interference between VMs (e.g. system bus / L3 cache may still be shared)
- No CPU sharing between VMs
- Uniprocessor scheduling theory directly applicable
- Easy to mix real-time and non-realtime VM payloads

- Amenable to heterogenous multicore SoCs
- Inflexible: #Cores ≥ #VMs → Can lead to poor utilization
- Sharing, if needed, can be difficult

\(^1\)for hardware solutions
HYPERVERSOR CPU ALLOCATION

- 2. Hierarchical scheduler
- Dynamic allocation of cores to VMs

+ More flexible
+ Controlled sharing of CPU and other resources possible
+ Better utilisation of resources
+ Applicable to uniprocessor systems
- More interference between VMs
- Scheduling needs more consideration
04
HYPERVERVISOR SCHEDULING
TIME FROM A VM’S POINT OF VIEW

- Computation time and observed “wall clock time“ differ
  - Slowdown due to virtualization (e.g. trap & emulate)
    - Makes virtual processor run slower
    - Compensate by allocating more budget
    → No problem for determinism
- Slowdown due to sharing of CPU with other VMs
  - Causes “Blackouts“
    (CPU not available when VM has work to do)
  - Need to adapt hypervisor scheduling to either avoid or cope
- Slowdown due to pollution of shared Caches / TLBs by other VMs
  - Makes virtual processor run slower following VM switch
  - Effect decays as CPU is “owned“ by VM for some time
  - May also leak information about other VM (covert channel)
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EFFECT ON LATENCY

- Real-time process running in VM may experience a “blackout”
- Worst case delay: $\Delta t_{del_j} = \Delta t_{sw} + \sum_{i \neq j} \Delta e_{vm_i} + \Delta t_{sw}$

Imposed jitter/delay is severe, but bounded
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LOCK HOLDER PREEMPTION PROBLEM

- Cause: Virtual CPU (vCPU) being preempted while holding a spinlock
- Guest OS is unaware of vCPU ↔ pCPU mapping
- May cause excessive CPU waste
- Similar to priority inversion problem

Countermeasures:
- “Helping” [FB08]: complex interaction patterns
- At VM scheduler level: always co-schedule VMs
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PROPORTIONAL SHARE SCHEDULING

- Default strategy with most hypervisors:
  - Pfair / proportional share scheduling
  - VMs receive share (percentage) of CPU(s)
- Idealised assumption: VM “sees” slower CPU, available at any time

→ Slowdown can (in theory) be compensated by allocating sufficient budget
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PROPORTIONAL SHARE SCHEDULING

- Idealised situation ...
  - ... is approximated
  - Precision increases with frequency
  - Limited by switch cost

- Rule of thumb: Switch frequencies above 1-10kHz lead to excessive overhead
  → Applicable to best effort and “slow” real-time systems
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Shortcomings from a real-time perspective:
- Scheduler is work conserving: idle VMs give up their time slice
  - Makes actual allocation unpredictable
  - Breaks (to some extent) VM isolation by opening covert channels
- Generally no admission test
  - per VM absolute budget could change at any time
- Targeted at best effort, greedy VMs
TIME PARTITIONING

- VMs have statically configured time slots (durations) within periodic major time frame
- (Different modes are possible)
- Time slots are enforced: exceeding budget is a violation
- Non-work conserving: VMs must "burn" budget when idle
- Simple enough for formal reasoning
- Targeted at real-time systems
PIKEOS SCHEDULER [KF14]

- Assign priority ranges to VMs
- Assign time domains\(^2\) (\(\tau_i\)) to VMs
- A VM is scheduled iff
  - it has the highest priority, \textbf{and}
  - its time domain is active

- Up to two time domains can be active at a time:
  - \(\tau_0\): background domain, always active
  - \(\tau_i, i = 1..N\): foreground domain, switched by partition schedule

- VMs from foreground or background domain selected by priority
- Guaranteed time partitioning, but also work conserving:
- Over-allocated budget not used by high priority, foreground real-time VMs falls back to low priority, background best-effort VMs

\(^2\)(represented by a set of ready queues, one per priority)
06
HIERARCHICAL SCHEDULING
SUPPORTING DIFFERENT VM CLASSES

- VM scheduler must be aware of the nature of task sets executing in a VM
- **Real-time**: must or should\(^3\) meet deadlines
- Two subclasses:
  - Time-driven: static schedule, typically periodic
  - Event-driven: scheduled in response to (unpredictable) events, (assumed to be sporadic)
- **Non real-time** (best effort): no need to meet deadlines, instead: try to utilise all resources ("greedy")
- Assumption: Each class uses a specific OS API
  - Guests and their VMs as a whole can be classified as one of:
    1. Time-driven, real-time (TRT)
    2. Event-driven, real-time (ERT)
    3. Non real-time (NRT)
- VM scheduler must guarantee sufficient resources for all real-time guests

\(^3\) "must" = "hard", "should" = "soft" real-time
SUPPORTING TIME-DRIVEN VMS

- Cause of VM delay: VMM schedule and local schedules not correlated

⇒ Synchronise VMM schedule and local schedules of time-driven VMs

- Define VMM schedule to “enclose” all time-driven local schedules

- Restrictions:
  - Local schedules must not overlap
  - Local schedules must use same (or harmonic) periods

- Low jitter (e.g. for PLCs)

Resulting “super schedule” is strictly a function of time
SUPPORTING EVENT-DRIVEN VMS

- Event-driven VMs need access to CPU at arbitrary times
  \[\Rightarrow\] Need ability to preempt current VM
- Conflicts with time-driven VMs
- Two choices:
  - Give event-driven VMs precedence over time-driven VMs
    \[\Rightarrow\] Time-driven VMs experience jitter and delays
  - Give time-driven VMs precedence over event-driven VMs
    \[\Rightarrow\] Event-driven VMs are delayed
- Classical dilemma: no generic solution (for uniprocessor architectures)
- Approach must be flexible enough to allow both choices on a case by case basis
- How to derive necessary period/budget for real-time VMs?
VM’s point of view:

1. \( P = \{1, \ldots, n\} \): Set of periodic tasks with:
   - Execution time \( \Delta e_i \)
   - Period \( \Delta p_i \)

2. Scheduled, e.g. by RMS (fixed prio)

Abstraction: equivalent representation at the hypervisor level: one periodic proxy process with parameters \( \Delta e_{prox}, \Delta p_{prox} \)
PROXY MODEL

- **VM's point of view:**
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RMS INTEGRATION

▶ RMS rule:

\[ \Delta p_i > \Delta p_j \iff \text{prio}(i) < \text{prio}(j) \]

▶ Concept of the proxy process:

1. To guarantee timeliness on the local level, set:
   \[ \Delta p_{prox} \leq \min(\Delta p_i) \forall i \in P \]
2. Map the time quantum \textit{not} used by the proxy to a "parasite process" \( \delta \), in the worst case of higher priority.
3. Since \( \Delta p_{\delta} \leq \Delta p_{prox} \leq \min(\Delta p_i) \forall i \in P \), \( \delta \) can be added to the set \( P \) as new task having the highest priority.

⇒ RMS remains applicable to new set
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⇒ RMS remains applicable to new set
Question: What are the lowest upper bounds on utilization of the process set \( \{\delta, 1, \ldots, n\} \)

- Derivation analogous to Liu/Layland (see [KZ09]):

\[
U_{\text{min}} = n \cdot \left( \sqrt[n]{\frac{2}{U_\delta + 1}} - 1 \right)
\]

\[
\lim_{n \to \infty} U_{\text{min}} = \ln \left( \frac{2}{U_\delta + 1} \right)
\]

- Where: \( U_\delta = \frac{\Delta e_\delta}{\Delta p_{\text{prox}}} \) is the CPU utilization by the parasite process \( \delta \)
POXY TASK PARAMETERS

- Proxy period (see above): $\Delta p_{\text{prox}} = \min(\Delta p_i)$
- Proxy execution time:

$$\Delta e_{\text{prox}} + \Delta e_\delta = \Delta p_{\text{prox}} \text{(see above)}$$

$$\Rightarrow U_{\text{prox}} = \frac{\Delta e_{\text{prox}}}{\Delta p_{\text{prox}}} = 1 - U_\delta$$

$$\Rightarrow \Delta e_{\text{prox}} = 2 \cdot \Delta p_{\text{prox}} \cdot \left(1 - \frac{1}{\left(\frac{u}{n} + 1\right)^n}\right)$$

$$\lim_{n \to \infty} \Rightarrow \Delta e_{\text{prox}} = 2 \cdot \Delta p_{\text{prox}} \cdot \left(1 - e^{-U}\right)$$

- Can compute $\Delta e_{\text{prox}}, \Delta p_{\text{prox}}$ for all VMs using RMS
- Input to global scheduler, planning using RMS or EDF

A similar derivation is also possible for EDF [Kai09]
07
CONTEXT SWITCH COST
SLEDGEHAMMER APPROACH

- Estimate switch cost
- Describe switch behaviour with a simple model
- "Calibrate" model with experimentally gathered data
- Cons/Pros:
  - imprecise
  - no proof (only empirical evidence)
  - simple computation
  - only superficial platform information required
- At any rate: better than neglecting ...
MODEL

- Computational Power, or Progress rate: $r(t)$
- Work (or Service): $W_{cpu}(t)$

$$W_{cpu}(t_1, t_2) = \int_{t_1}^{t_2} r(\tau) d\tau$$

- Equivalent constant workload (i.e. $r(t) = \bar{r}$):

$$W(t_1, t_2) = (t_2 - t_1) \cdot \bar{r}$$
SWITCH OVERHEADS

- Execution time lost by task switching
  - Activity of other processes (not overhead)
  - Scheduler activity (Overhead)
- Assumption: Fixed scheduler execution time ($\Delta t_{sw}$)

⇒ Cost per scheduler invocation:

$$W_{sched} = \Delta t_{sw} \cdot \bar{r}$$

- On process switch$^4$: more overhead
- Both can be accounted to processes

$^4$(Note: Process switch $\neq$ scheduler invocation)
PROCESS SWITCH COST

- Process switch cost: caused by Cache-/TLB-misses
- No discrete time window but "slowdown" of CPU, i.e. temporarily lowered progress rate

Cost per process switch:

\[ W_{sw}(t) = t \cdot \bar{r} - \int_{0}^{t} r_{sw}(\tau) \, d\tau \]

Relative loss:

\[ O_{sw}(t) = 1 - \frac{1}{t} \int_{0}^{t} \frac{r_{sw}(\tau)}{\bar{r}} \, d\tau \]

Process switch at \( t = 0 \)
PAYLOAD SHARE

- Share of computational power consumed by payload:

\[ f(t) := \frac{r_{sw}(t)}{r} \]

- Thus:

\[ O_{sw}(t) = 1 - \frac{1}{t} \int_{0}^{t} f(\tau) d\tau \]

- Problem: \( f(t) \) is unknown, however
  - best case: \( f(t) = 1 \)
  - worst case: \( f(t) = f_{min} > 0 \)
  - realistic case: somewhere between ..
APPROXIMATING PAYLOAD SHARE

- Use time-dependent functions $f(t)$, e.g.:
  - "cache flooding" (worst case) ...
    \[
    f_{\text{flood}}(t) = \begin{cases} 
    f_{\text{min}}, & 0 \leq t < t_s \\ 
    1, & t \geq t_s 
    \end{cases}
    \]
  - ... or linear ...
    \[
    f_{\text{lin}}(t) = \begin{cases} 
    f_{\text{min}} + \frac{1-f_{\text{min}}}{t_s} \cdot t, & 0 \leq t < t_s \\ 
    1, & t \geq t_s 
    \end{cases}
    \]
  - ... or exponential function ...
    \[
    f_{\text{exp}}(t) = 1 + (f_{\text{min}} - 1) \cdot e^{-kt}
    \]
  - all parametrised by $f_{\text{min}}, t_s$

⇒ Can compute loss per process switch

- Use different $f(t)$ depending on timing requirements, e.g.
  - "hard" real-time → use $f_{\text{flood}}(t)$
  - "soft" real-time → use $f_{\text{lin}}(t)$ or $f_{\text{exp}}(t)$
GOALS AND METHODS

Question: How to find appropriate values for \((t_s, f_{\text{min}}, \text{etc.})\)?

Empirical approach: Measure, 2 goals:

1. Demonstrate/validate worst case behaviour ("flooding")
2. Determine realistic parameters

Method:

- Bring caches into a defined state (invalidate / read-fill / write-fill)
- Read- or write-access data in a previously uncached memory region of configurable size ("working set")
- Measure: Time used for a given (variable) number of accesses
RESULTS

▶ MPC 5200 @ 400MHz: Simple, single-level cache, 16kB

<table>
<thead>
<tr>
<th>Testcase</th>
<th>WSS</th>
<th>Cache</th>
<th>$f_{\text{min}}$</th>
<th>$t_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>consec_wr</td>
<td>2k</td>
<td>dirty</td>
<td>0.05</td>
<td>17$\mu$s</td>
</tr>
<tr>
<td>consec_wr</td>
<td>4k</td>
<td>dirty</td>
<td>0.05</td>
<td>31$\mu$s</td>
</tr>
<tr>
<td>consec_wr</td>
<td>8k</td>
<td>dirty</td>
<td>0.05</td>
<td>59$\mu$s</td>
</tr>
<tr>
<td>consec_wr</td>
<td>16k</td>
<td>dirty</td>
<td>0.05</td>
<td>116$\mu$s</td>
</tr>
<tr>
<td>consec_wr</td>
<td>2k</td>
<td>invd</td>
<td>0.13</td>
<td>10$\mu$s</td>
</tr>
<tr>
<td>consec_wr</td>
<td>4k</td>
<td>invd</td>
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<td>19$\mu$s</td>
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<tr>
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</tr>
</tbody>
</table>

invd = cache invalidated, dirty = cache flood-filled

▶ $t_s \sim WSS$
▶ $f_{\text{min}}$ between 5% and 13%

⇒ Matches model behaviour
SOC EXAMPLES

Testcase: writing to adjacent cache lines

inv = Cache invalidated, dirty = cache flood-filled

<table>
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<th>Cache</th>
<th>$f_{\text{min}}$</th>
<th>$t_s$</th>
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<tr>
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<td>16k</td>
<td>dirty-w</td>
<td>0.063</td>
<td>60 $\mu$s</td>
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<tr>
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<td>i.MX6</td>
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<td>210 $\mu$s</td>
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<tr>
<td>i.MX6</td>
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<td>inv-w</td>
<td>0.134</td>
<td>29 $\mu$s</td>
</tr>
<tr>
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<td>0.124</td>
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</tr>
<tr>
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<td>inv-w</td>
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<td>13 $\mu$s</td>
</tr>
<tr>
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<tr>
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<td>40 $\mu$s</td>
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<tr>
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<td>$\approx$470 $\mu$s</td>
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<td>dirty-w</td>
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<td>208 $\mu$s</td>
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<tr>
<td>KZM</td>
<td>64k</td>
<td>inv-w</td>
<td>$\approx$0.18</td>
<td>312 $\mu$s</td>
</tr>
</tbody>
</table>

$\triangleright$ Normalised values (i.MX6):

$\triangleright$ $t_s$ grows with "working set"
(roughly proportional ..)

$\triangleright$ $f_{\text{min}}$ between (here) 5% und 34%,
depending on WSS
(due to 2-level cache)

$\Rightarrow$ Qualitatively: expected behaviour
SCHEDULER SIMULATION

- “Lowest lag first” proportional share scheduler
- Cache load simulations: linear, exponential and flood
- Configured with $f_{min}$, $t_s$ as measured on i.MX6

⇒ Shows trade off between continuity ↔ switch cost
⇒ In the given case (i.MX6), switch frequencies higher than $\approx 2$-3 kHz lead to excessive overheads!
⇒ Similar results for other platforms [Kai08]

2 Tasks, 50% CPU each
Assumed scheduler exec time: $1\mu s$
UPSHOT

- Processor performance can drop down to ~ 5% (worst case) if context switches occur frequently
- To compensate in such cases, budgets for critical real-time VMs must be increased accordingly
- Less critical tasks can use a less pessimistic payload share function, resulting in less overhead
- Since overheads and slowdowns are attributed to individual VMs, other VMs are not affected (except for the global admission test)
08
SUMMARY AND CONCLUSION
SUMMARY

Recommendations how to avoid or cope with ... 

- Slowdown due to sharing of CPU with other VMs
  ▶ For “slow“ real-time tasks ($\Delta p_{prox} \geq \sim 100\, ms$):
    ▶ just use standard proportional scheduling
    ▶ however, make sure sure budget can be guaranteed (e.g. static admission test at system configuration time)
  ▶ For “fast“ real-time tasks ($\Delta p_{prox} < \sim 100\, ms$):
    ▶ increase budget to compensate for switch costs
    ▶ use time partitioning to enforce budgets
    ▶ for time-triggered tasks: use “enclosing super schedule“
    ▶ for event-triggered tasks: if possible, assign to core(s) different from event triggered tasks
SUMMARY

Recommendations how to avoid or cope with ...

- Slowdown due to pollution of shared caches / TLBs
  ▶ (again,) increase budget to compensate for switch costs
  ▶ partition caches (not covered here)
  ▶ for security-sensitive tasks:
    ▶ force cache flush (in the kernel) before switching contexts
    ▶ enforce consumption of full budget for every job execution to avoid cache side channels
CONCLUSION

- Achieving hypervisor temporal determinism is possible!
- However, applicability of common hypervisors intended for server consolidation is limited:
  - Put significant effort into unneeded features, (thus increasing the amount of trusted code)
  - Fail to guarantee timely scheduling for “fast“ real-time workloads
- Classification and corresponding treatment of different workloads is necessary
- External requirements of real-time workloads can be computed from their task parameters
REFERENCES
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