Periodic Task Mining in Embedded System Traces

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Real-Time Embedded System Group

UNIVERSITY OF WATERLOO

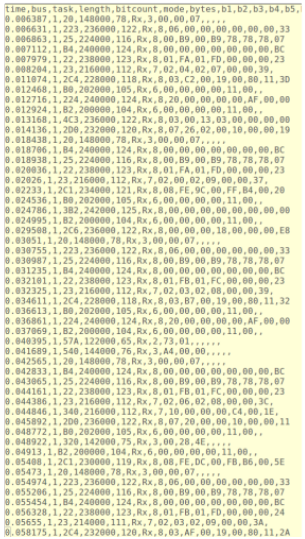
April 20, 2017

PeTaMi (PEriodic TAsk MIner)

Real-Time
Embedded System

execution →

Trace



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0.006631,1,223,236000,122,Rx,8,06,00,00,00,00,00,00,33
0.006063,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.007112,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
0.007979,1,22,238000,123,Rx,8,01,FA,01,FD,00,00,00,23
0.008204,1,23,216000,112,Rx,7,02,04,02,07,00,00,39,
0.011074,1,2C4,228000,118,Rx,8,03,C2,00,19,00,80,11,3D
0.012468,1,B0,202000,105,Rx,6,00,00,00,00,00,11,00,,
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0.018706,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
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0.024786,1,3B2,242000,125,Rx,8,00,00,00,00,00,00,00,00
0.024995,1,B2,200000,104,Rx,6,00,00,00,00,00,11,00,,
0.029508,1,2C6,236000,122,Rx,8,00,00,00,18,00,00,00,E8
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0.031235,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
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0.032325,1,23,216000,112,Rx,7,02,03,02,08,00,00,39,
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0.043065,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.044161,1,22,238000,123,Rx,8,01,FB,01,FC,00,00,00,23
0.044386,1,23,216000,112,Rx,7,02,06,02,08,00,00,3C,
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0.055206,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.055454,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
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0.058175,1,2C4,232000,120,Rx,8,03,AF,00,19,00,80,11,2A
```

PeTaMi →

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- task_1Z1: T=8ms, RTP=[2ms, 0.4ms, 1.5ms]

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Real-Time
Embedded System

execution →

Trace

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0.012468,1,B0,202000,105,Rx,6,00,00,00,00,00,11,00,,
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0.013168,1,4C3,236000,122,Rx,8,03,00,13,03,00,00,00,00
0.014136,1,2D0,232000,120,Rx,8,07,26,02,00,10,00,00,19
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0.034611,1,2C4,228000,118,Rx,8,03,B7,00,19,00,80,11,32
0.036613,1,B0,202000,105,Rx,6,00,00,00,00,00,11,00,,
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0.037069,1,B2,200000,104,Rx,6,00,00,00,00,00,11,00,,
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A solution for **reverse engineering** Real-Time Embedded Systems (RTES):

- standalone tool, or
- part of a comprehensive framework

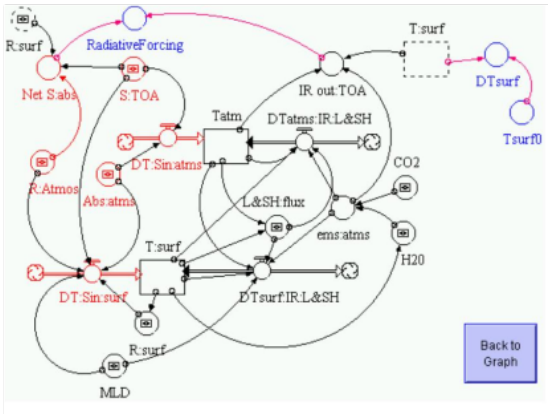
Reverse Engineering (RE)

"(Software) reverse engineering is the process of analyzing a subject system to create representations of the system at a higher level of abstraction" [1]

System

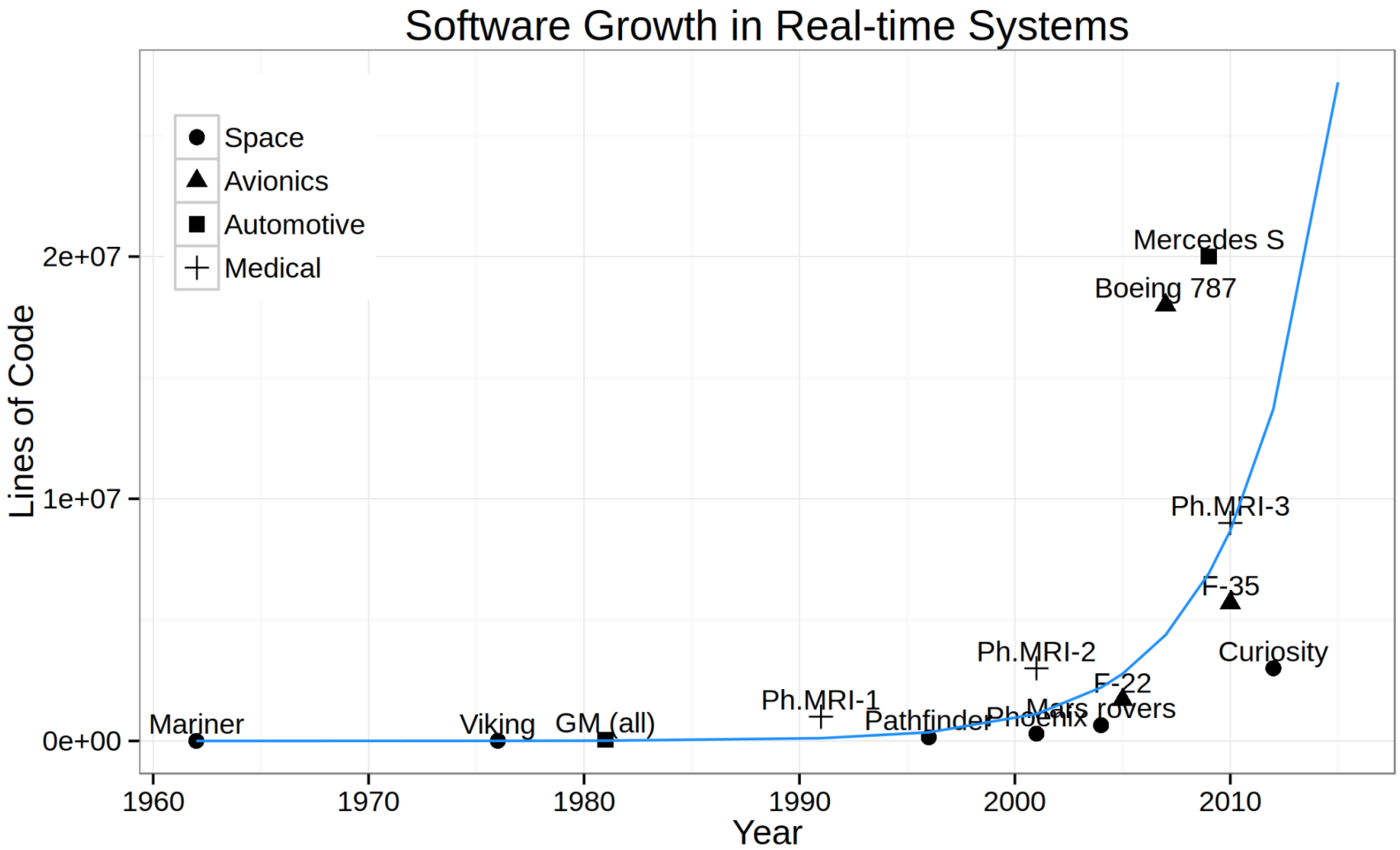
reverse engineering

System model



- Traditionally used in the domain of desktop and enterprise software

[1] Chikofsky EJ, Cross JH. "Reverse engineering and design recovery: A taxonomy". IEEE software 7.1 (1990): 13-17.



Sources:

- Charette RN. "This car runs on code". IEEE spectrum. 2009 Feb 1;46(3):3.
- Holzmann GJ. "Landing a spacecraft on Mars". IEEE software. 2013 Mar;30(2):83-6.
- Hofland L, van der Linden J. "Software in MRI Scanners". IEEE software. 2010 Jul 1;27(4):87.

Complex RTES

Need of software models for:

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Reverse engineering tools tailored for RTES are needed

Characteristics of a Reverse Engineering Tool

- Representation of a system
  - Finite state machine;
  - Petri net;
  - Regular expressions;
  - UML model;
  - and others...

- Extraction of information from a system
  - Static: from source code;
  - Dynamic: from traces;
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PeTaMi (PEriodic TAsk MIner)

Real-Time
Embedded System

execution →

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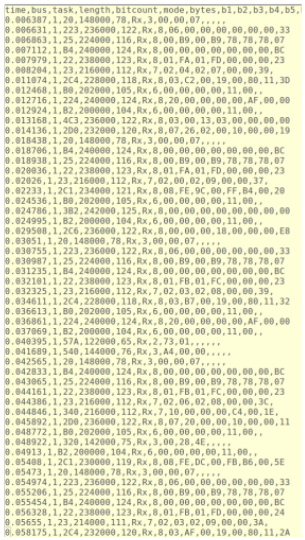

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RTES Execution Trace

timestamp event

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24889590208,00,THREAD,THRUNNING,9,1,,,,,,,,,,,,,,,,,,,24,2,,"",proc/b
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RTES Execution Trace

fields

timestamp event

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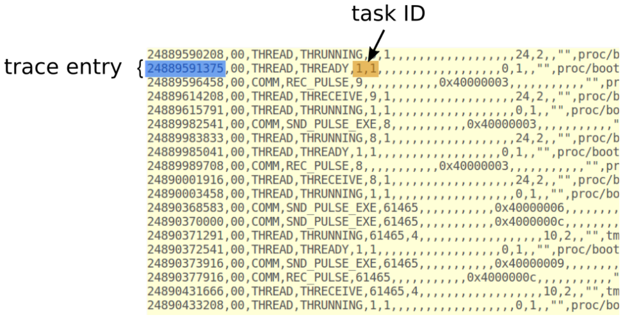
RTES Execution Trace



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24890433208,00,THREAD,THRUNNING,1,1,,,,,,,,,,,,,,,,,,,0,1,,"",proc/bo
```
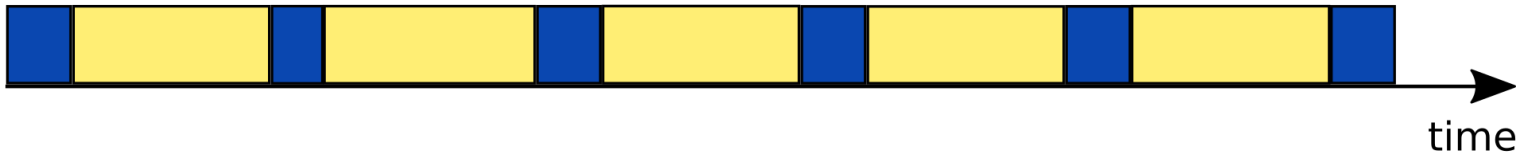

- *Trace*: chronologically ordered list of trace entries;
- *Trace entry*: tuple <timestamp, task ID>;
- *Task ID*: conjuction of fields that uniquely identify the task.

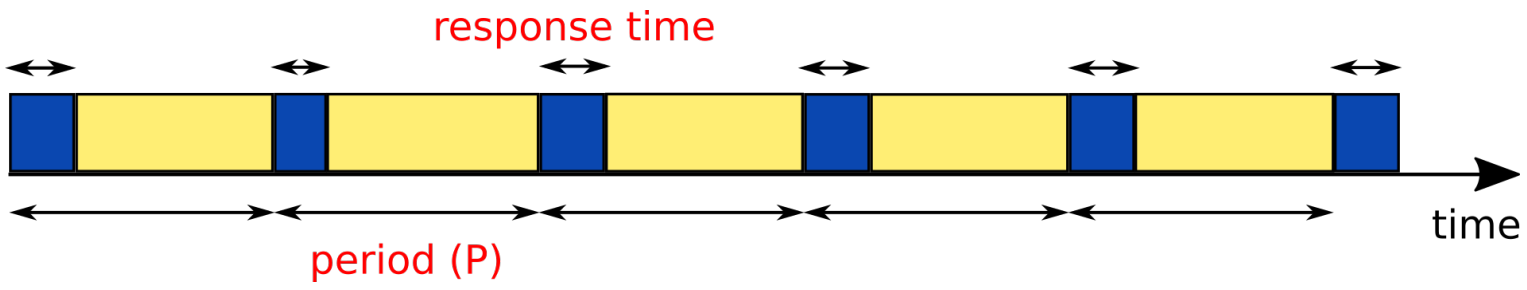
A Real-Time Task



A timeline view of execution of a real-time task on a CPU:

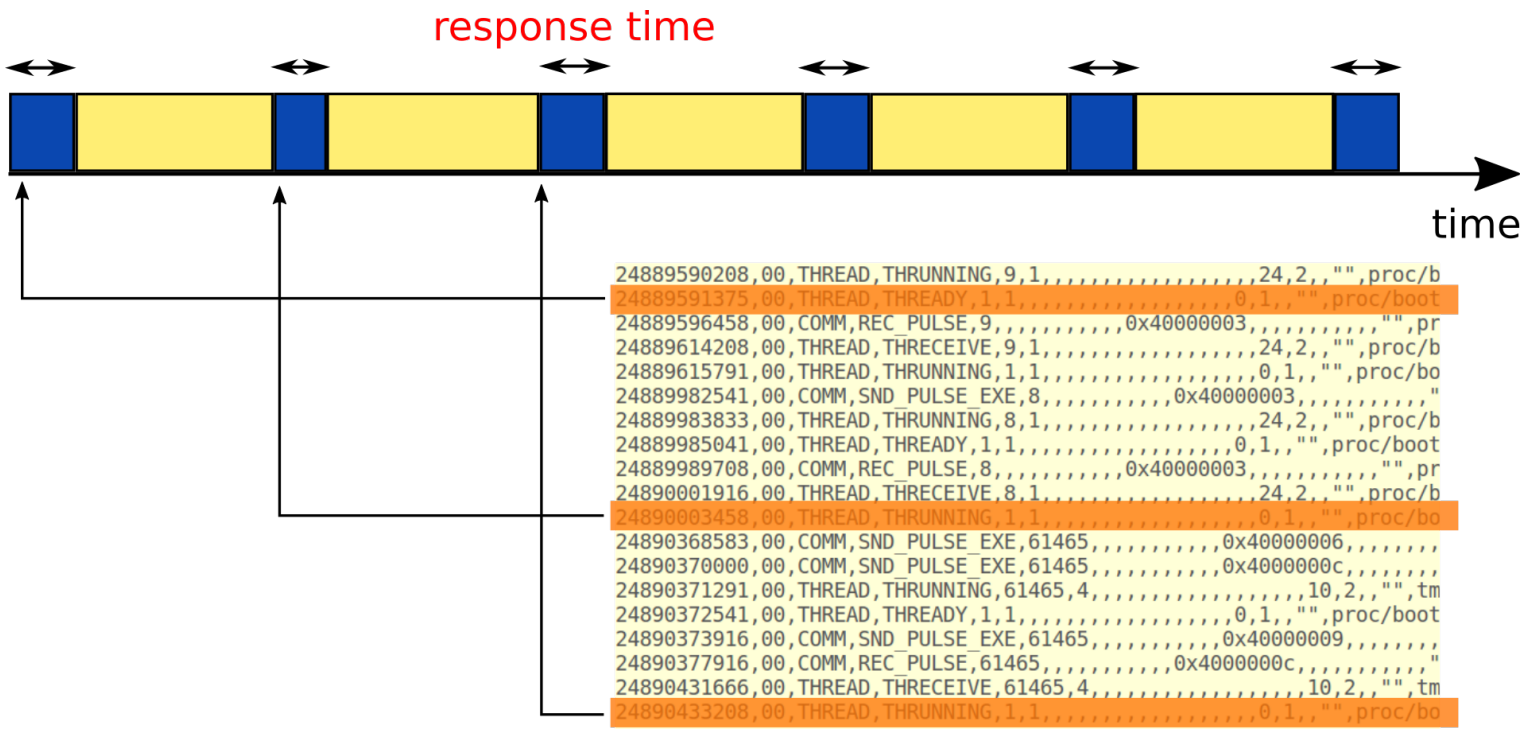
- blue boxes: CPU is executing the task;
- yellow boxes: CPU is idle or executing other tasks.

A Real-Time Task



- *Task*: a recurrent program that executes a sequence of jobs;
- *Periodic task* releases jobs with a fixed interval of time;
- *Response time*: time between when a task's job is released and when it is completed;

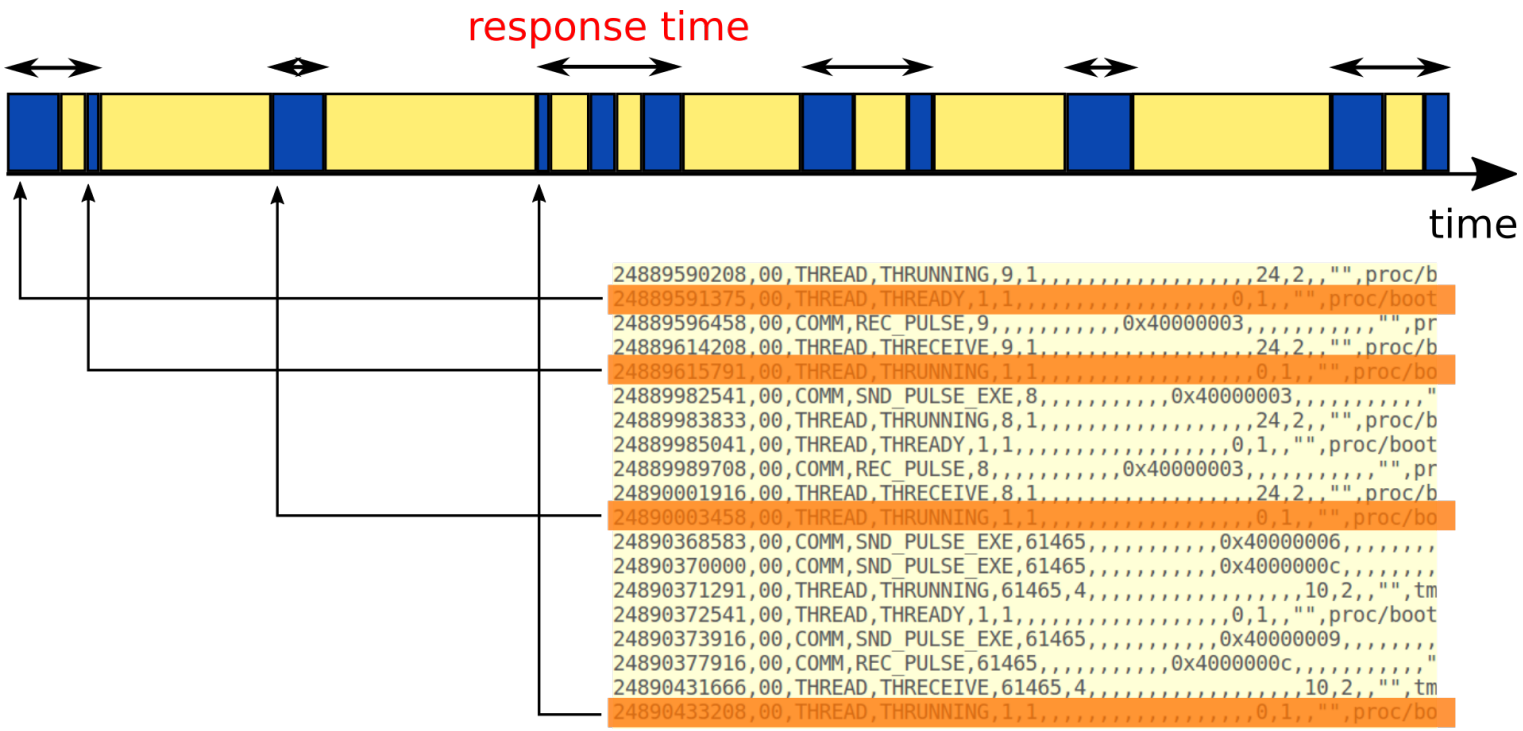
A Real-Time Task



Trace entries of a real-time task:

- nonpreemptive OS: one per job;

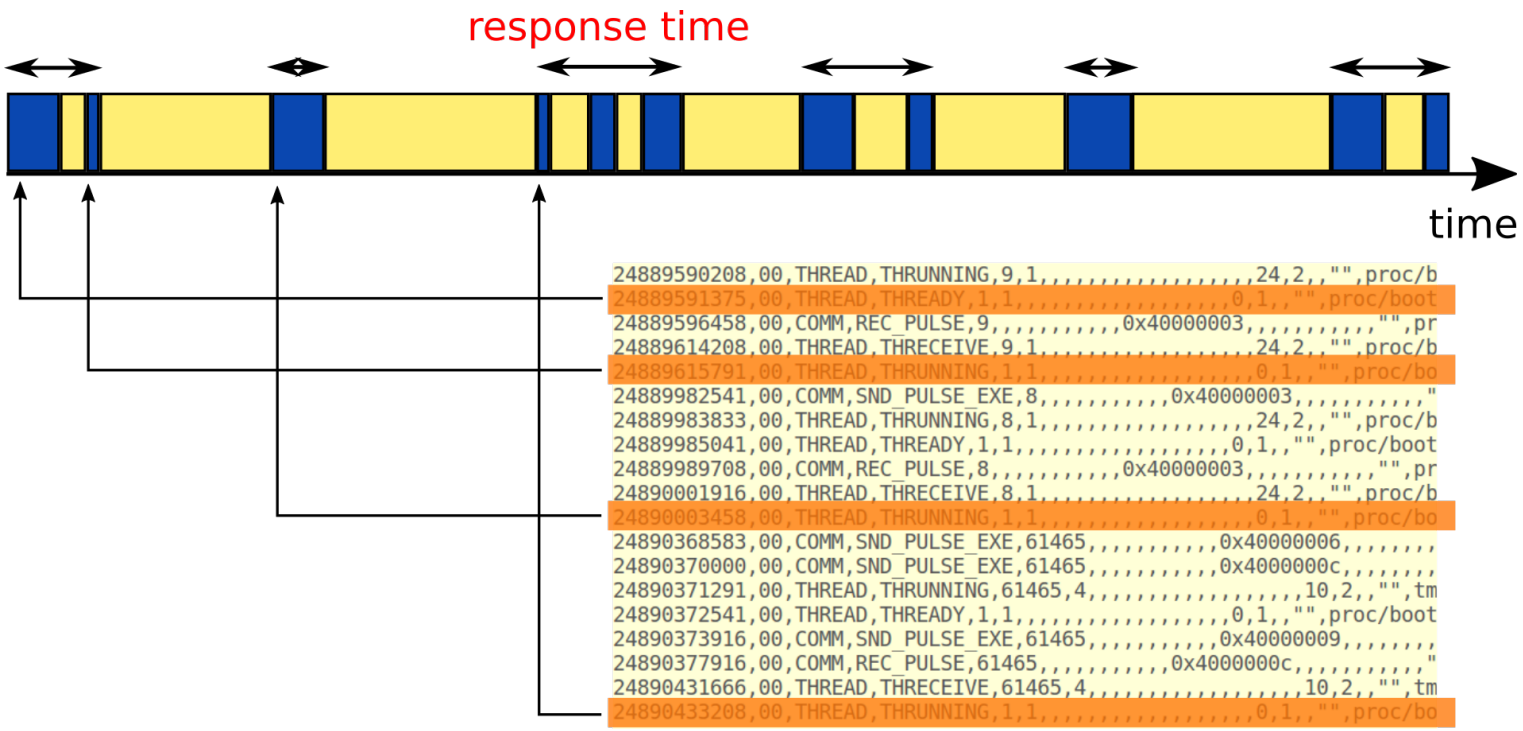
A Real-Time Task



Trace entries of a real-time task:

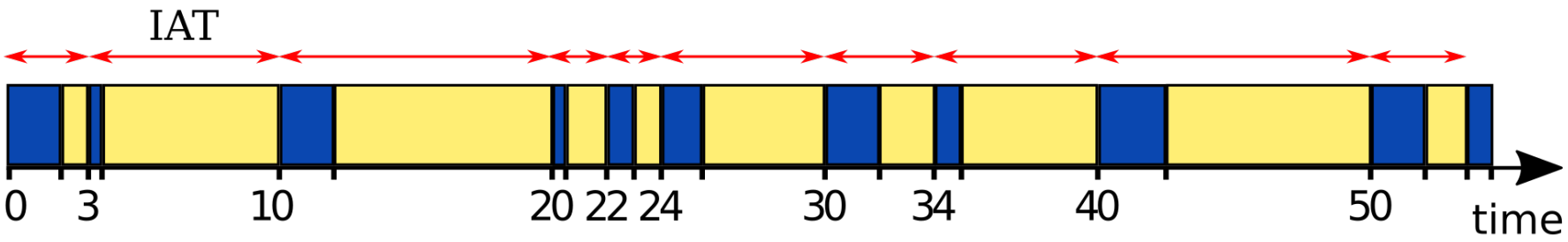
- nonpreemptive OS: one per job;
- preemptive OS: one **<u>or more</u>** per job;

A Real-Time Task



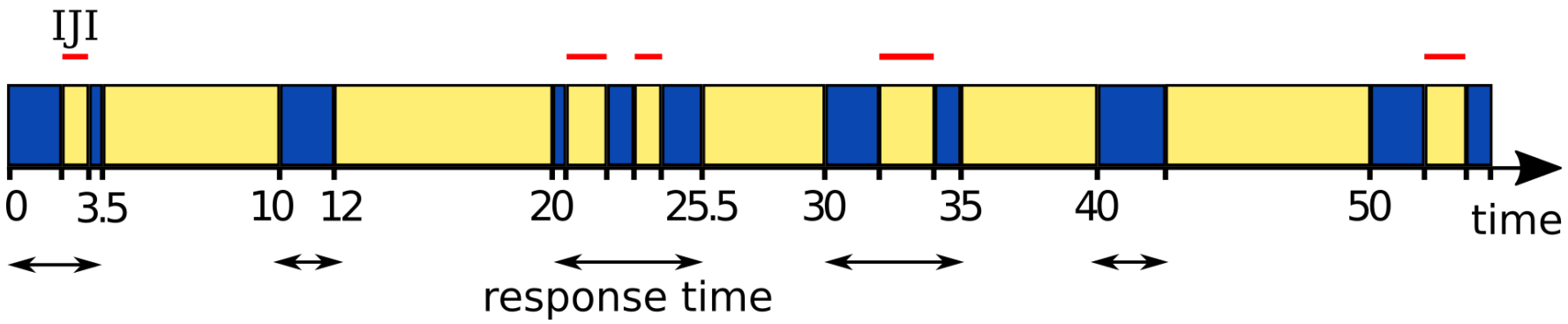
Problem: detect if a task is periodic from its trace entries.

Terminology



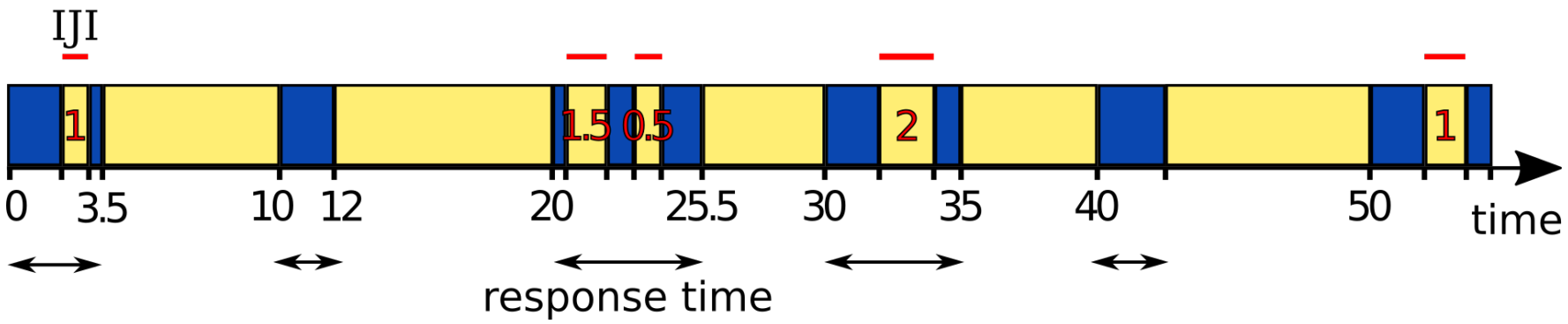
- Inter-Arrival Time (**IAT**): between consecutive task invocations;

Terminology



- Inter-Arrival Time (**IAT**): between consecutive task invocations;
- Intra-Job Interval (**IJI**): between consecutive task executions within a job;

Terminology



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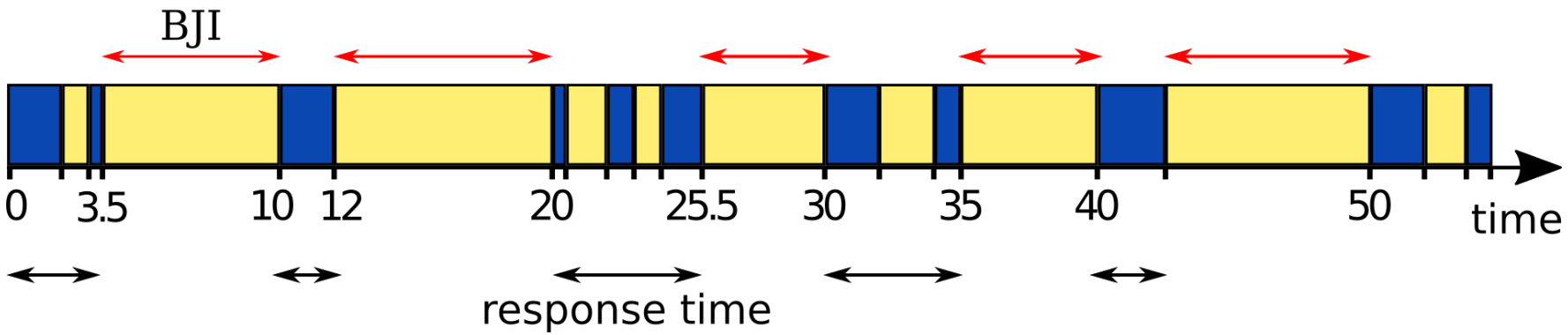

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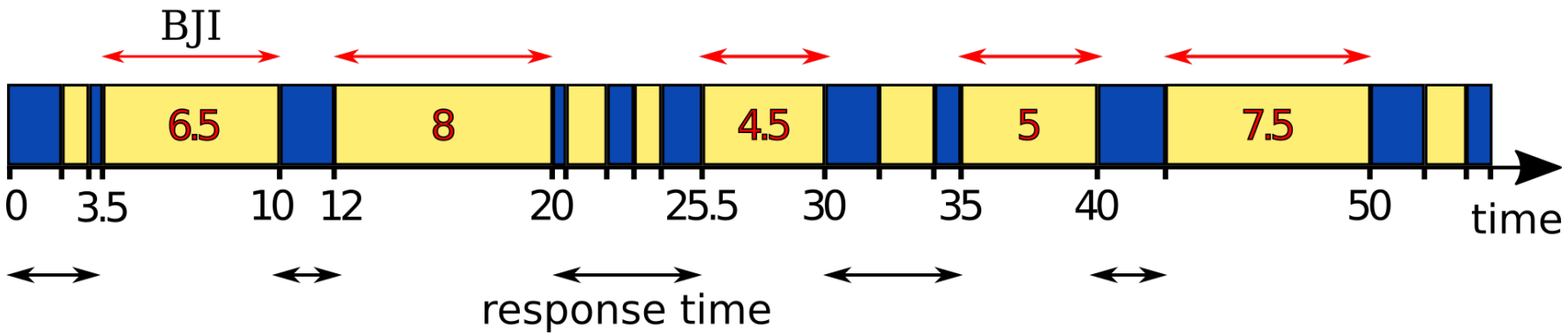

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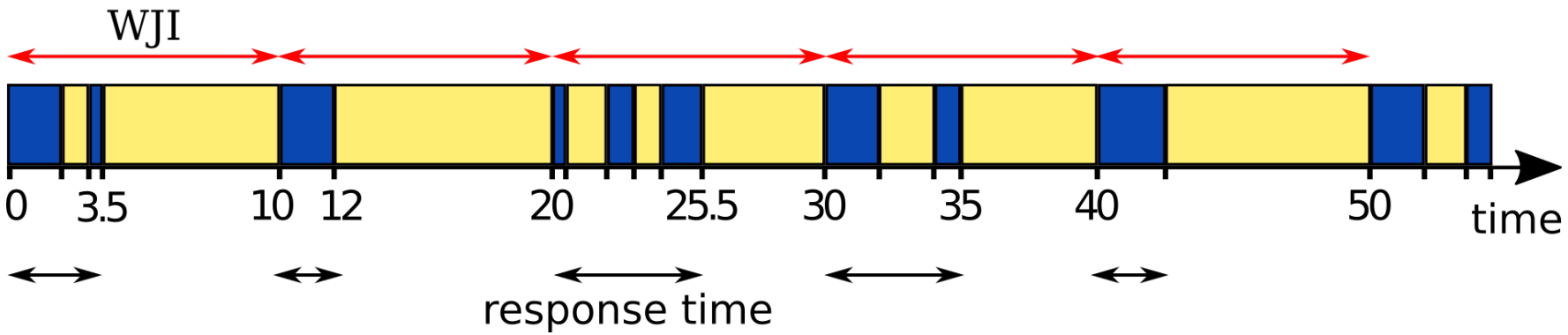

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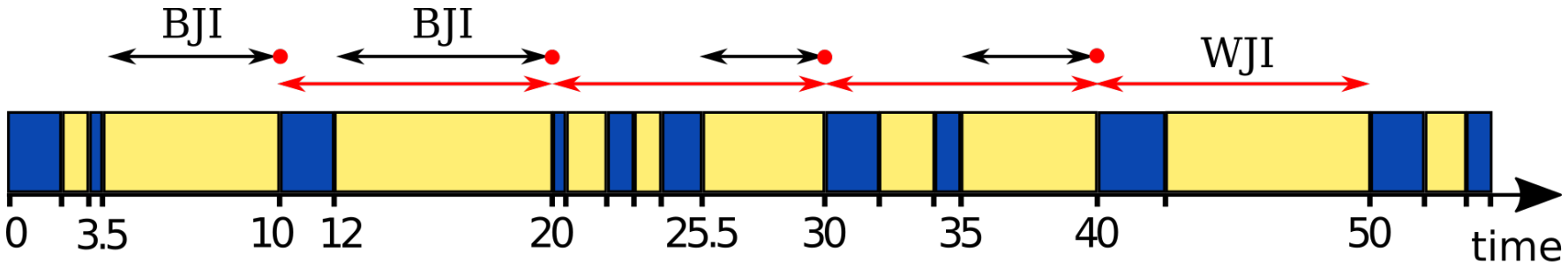
- Whole-Job Interval (**WJI**): between first task invocations of two consecutive jobs.

WJIs of a periodic task have $\sim$ same value.

Terminology



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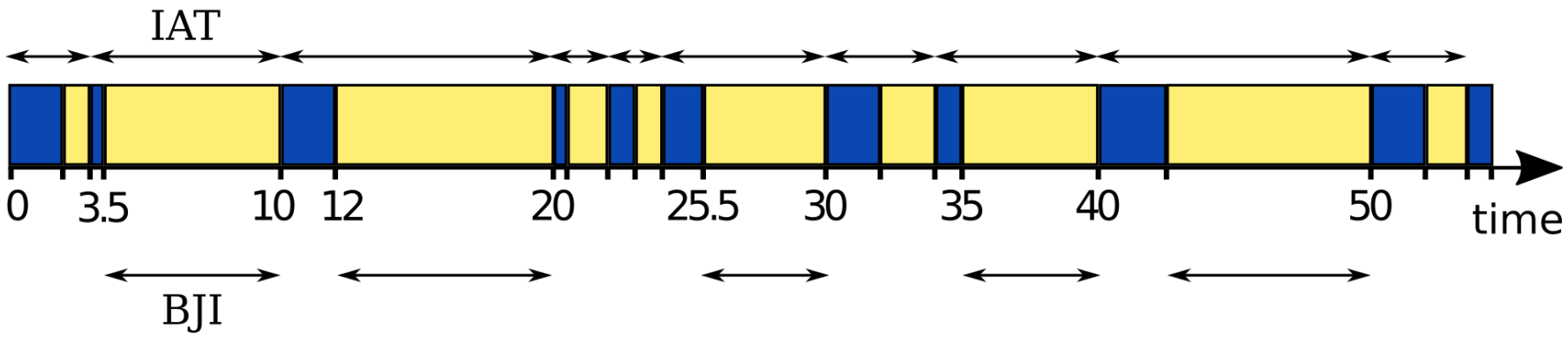
WJIs can be extracted from BJIs.

Terminology



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WJIs of a periodic task have $\sim$ same value.

WJIs can be extracted from BJIs.

Problem: extract BJIs from IATs.

The Assumption

If we let a periodic task τ execute for a considerable amount of time, then the mean duration of τ's *BJI*s will be larger than the mean duration of τ's *IJI*s.

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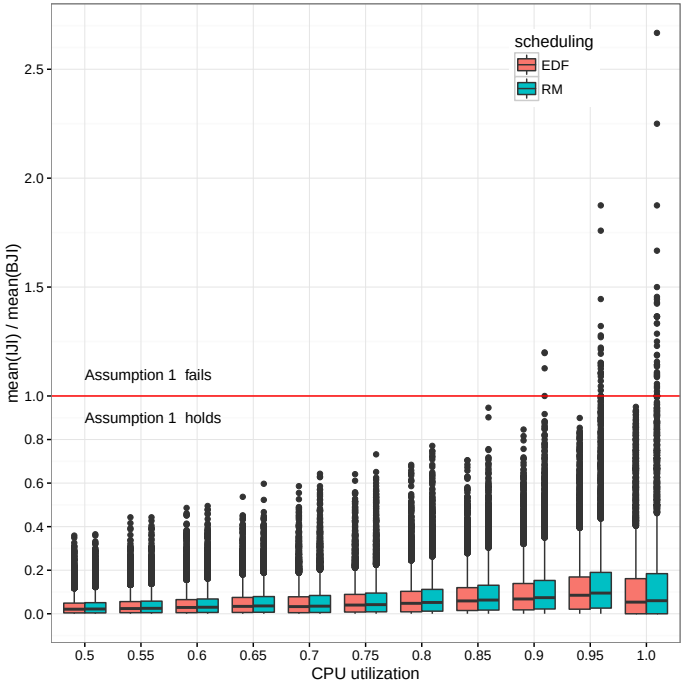
If we let a periodic task τ execute for a considerable amount of time, then the mean duration of τ's *BJI*s will be larger than the mean duration of τ's *IJI*s.

Simulation:

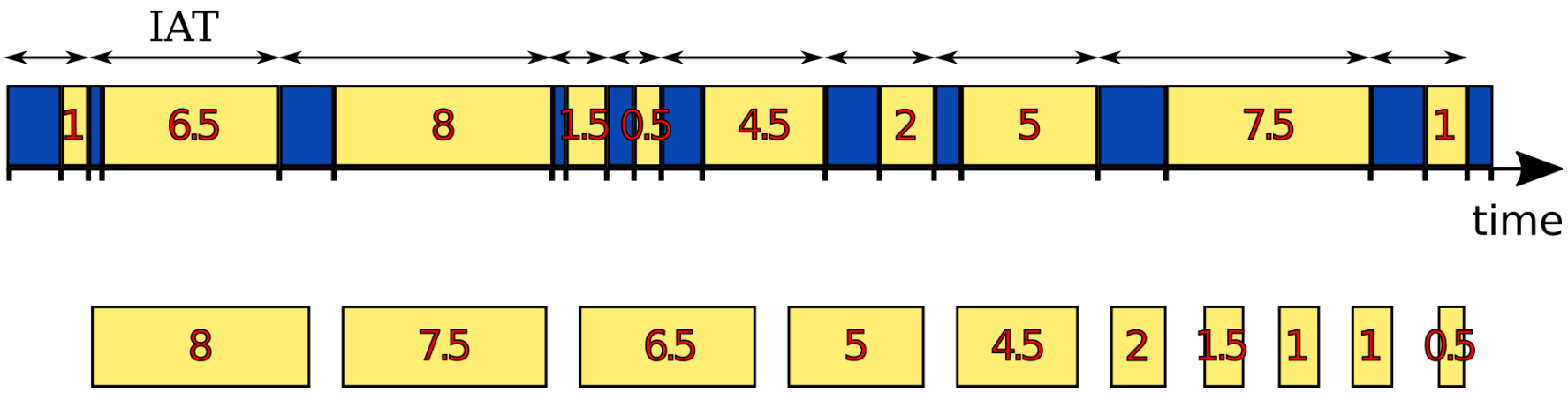
- 1000 task sets;
- 10^7 time units;
- random # of tasks per task set;
- random task's execution time;
- utilization: $[0.5, 0.55, 0.6, \ldots, 1.0]$;
- periods computed with UUniFast algorithm [2]



Unsafe RTES: CPU utilization $> 70\%$.

[2] Bini E, Buttazzo G. "Measuring the performance of schedulability tests". Real-Time Systems, 30(1-2):129-154, 2005.

Mining Periodic Tasks from RTES Traces



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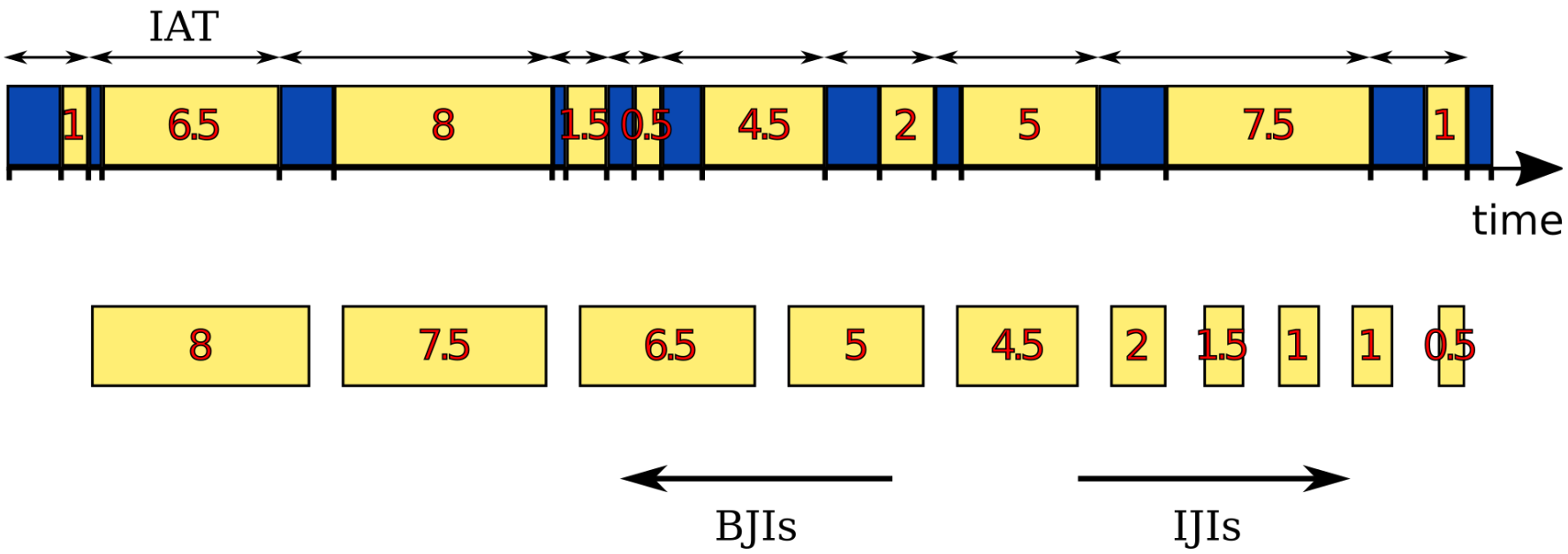

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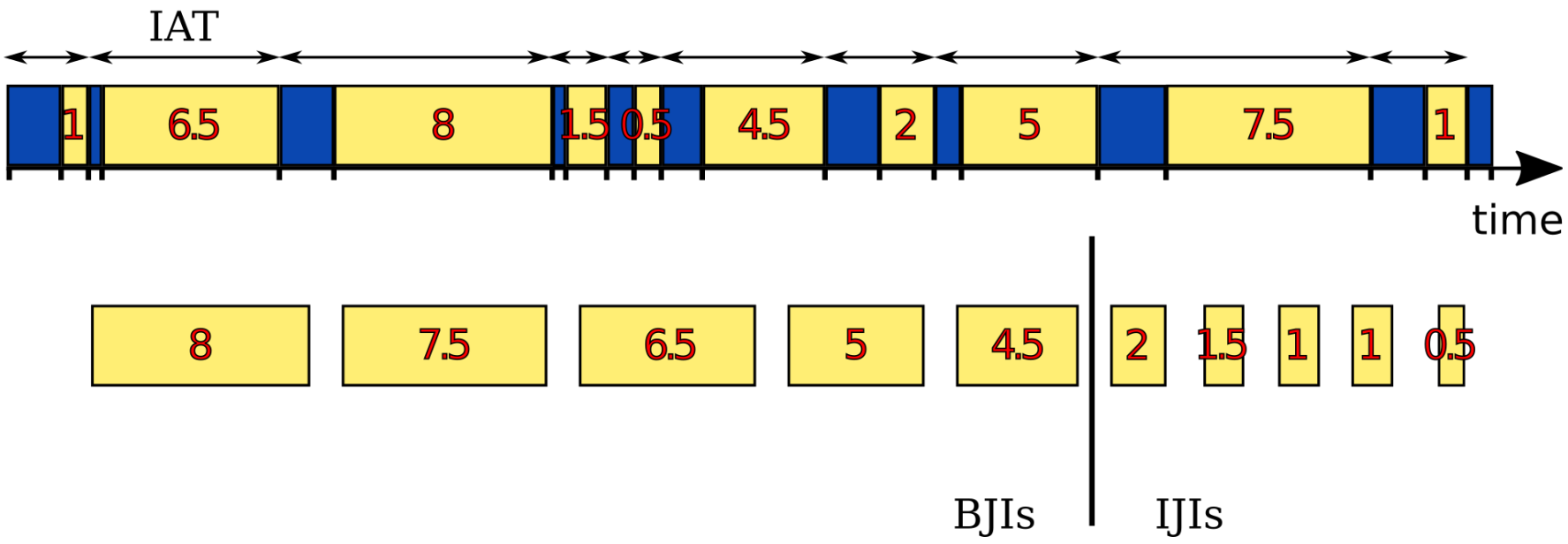

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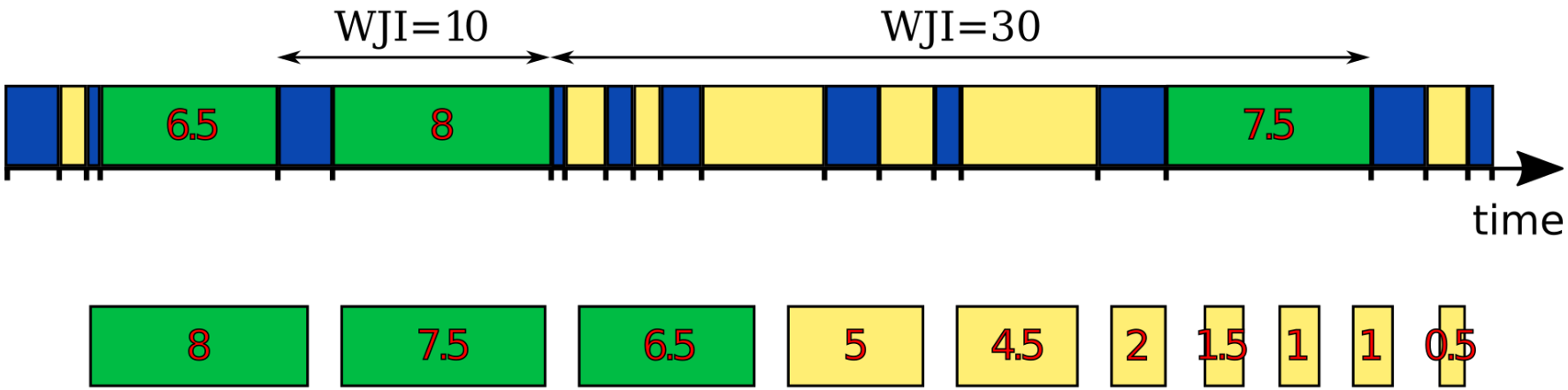

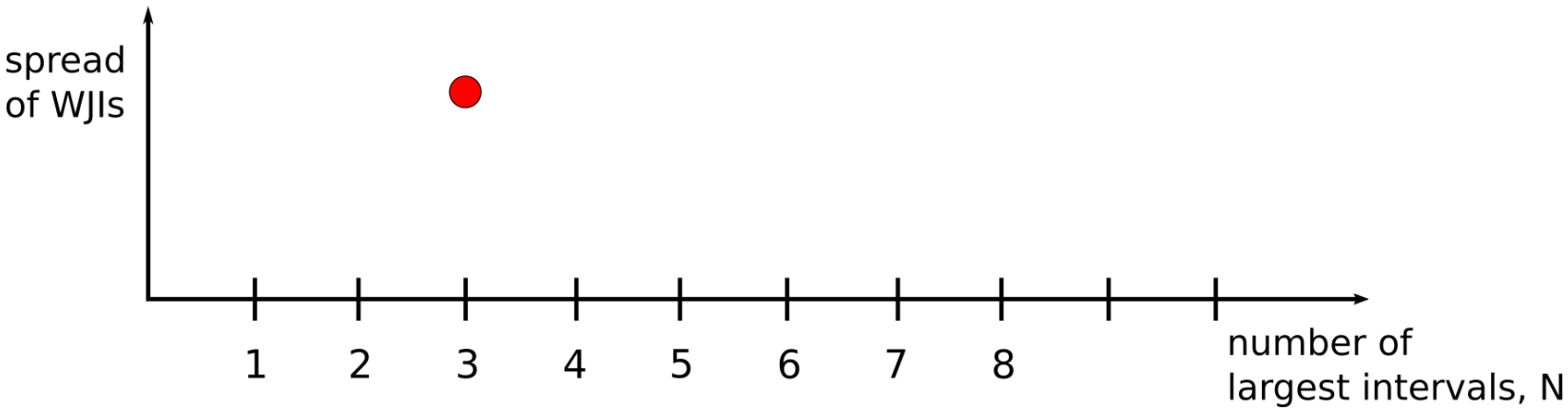

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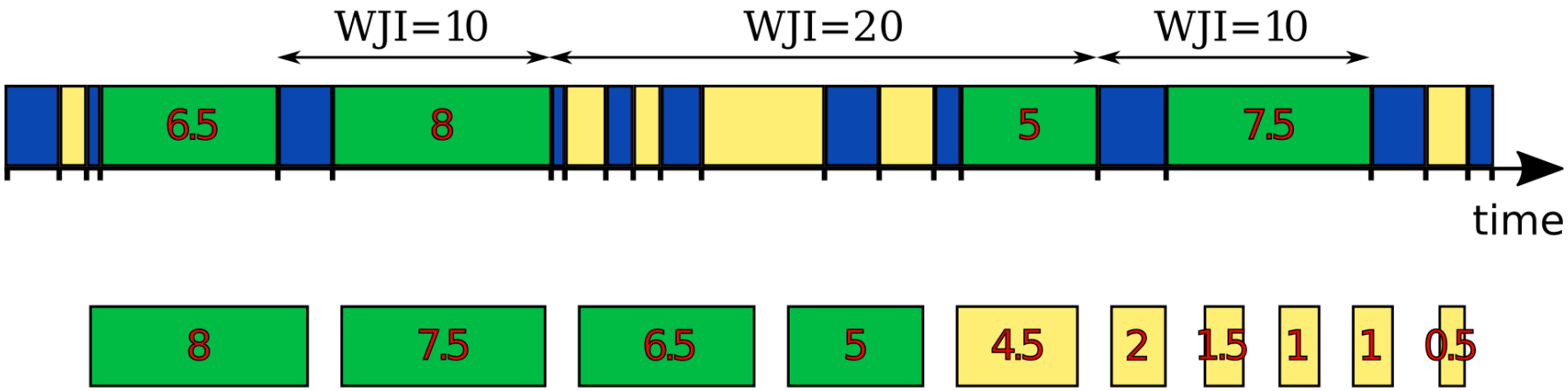

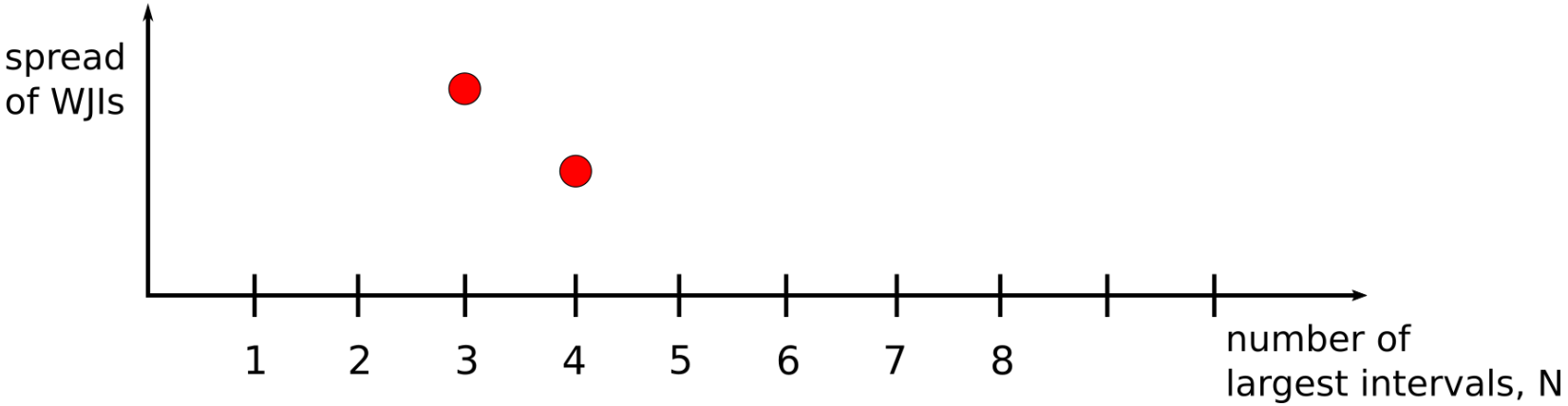

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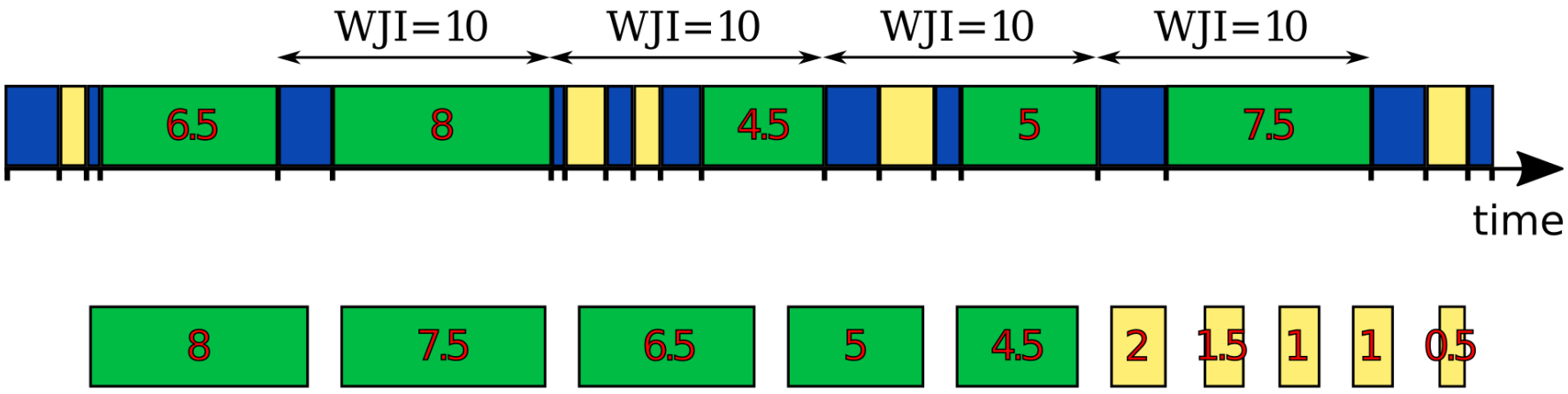

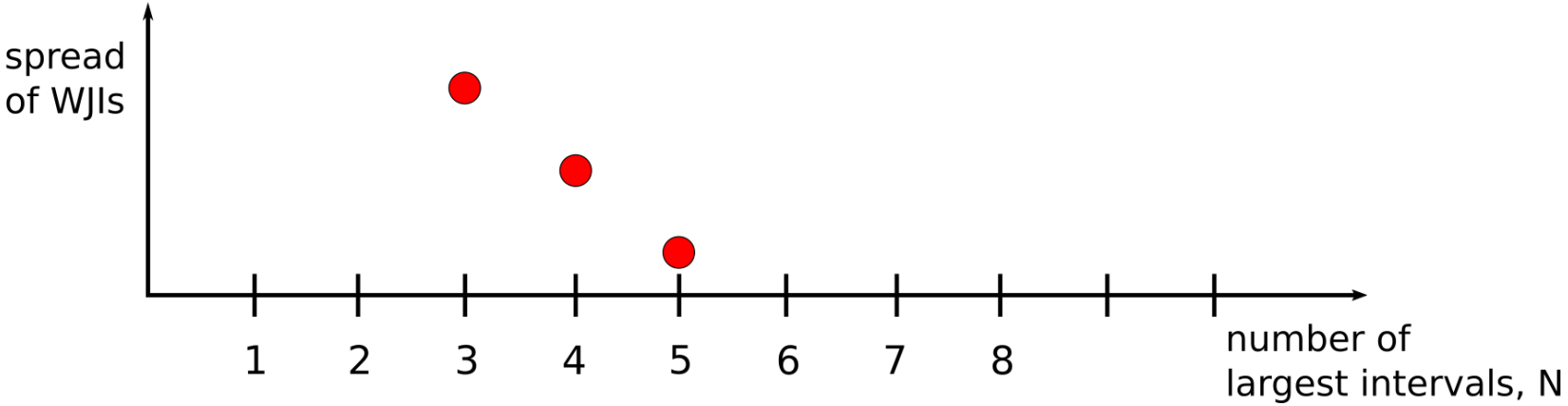

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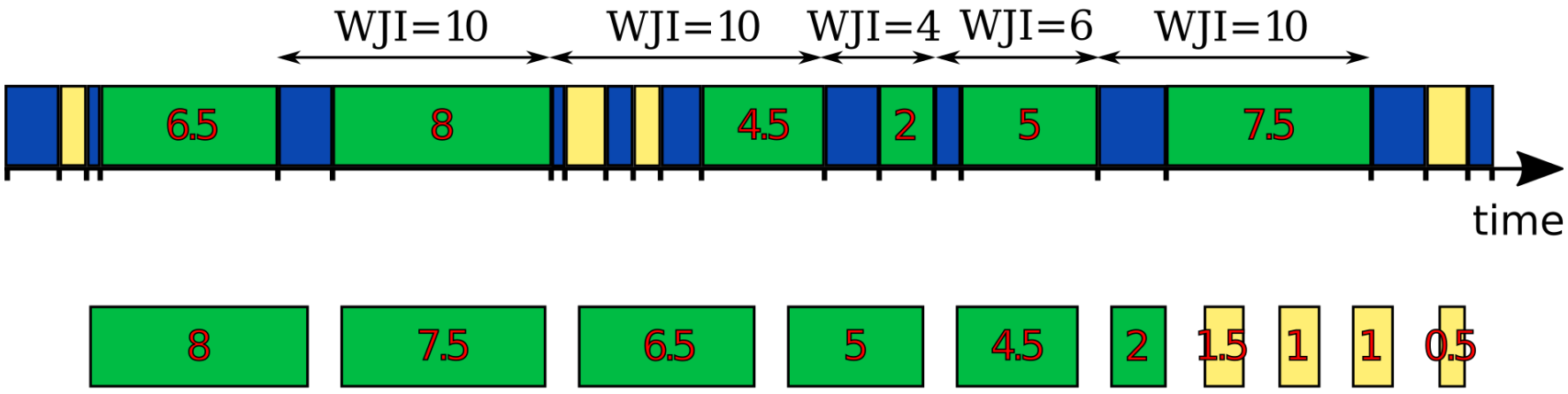

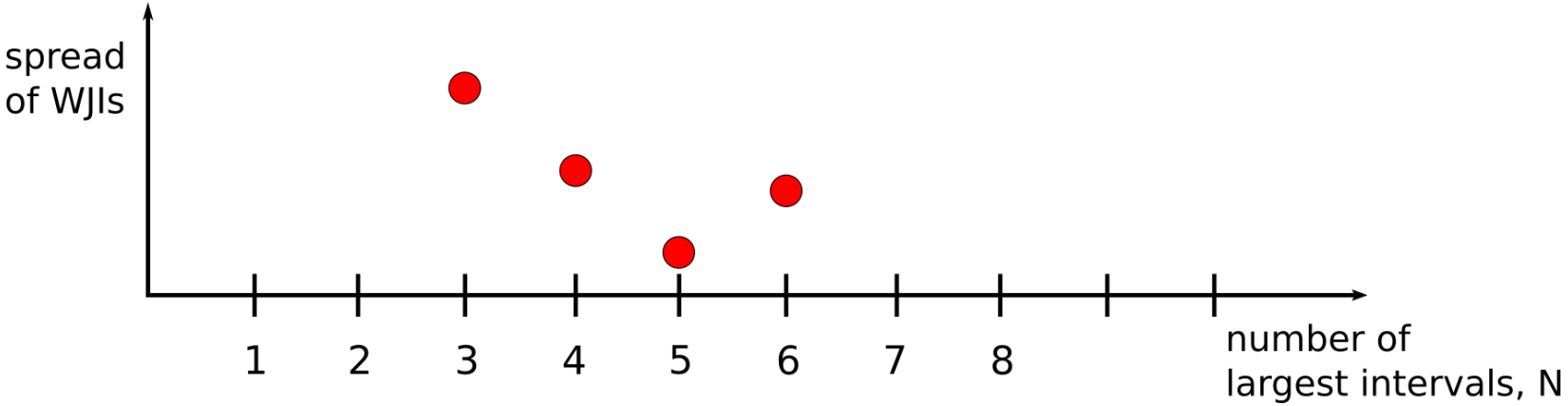

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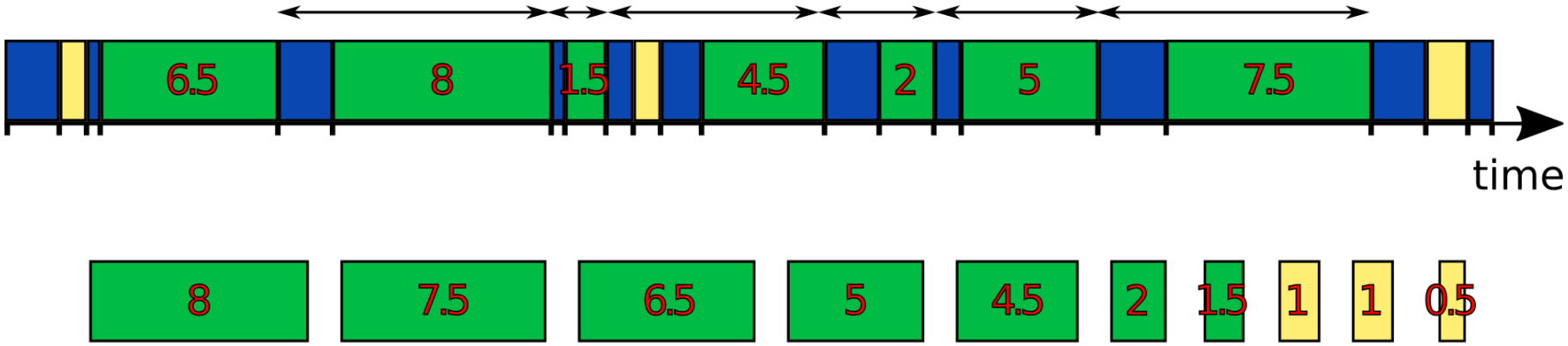

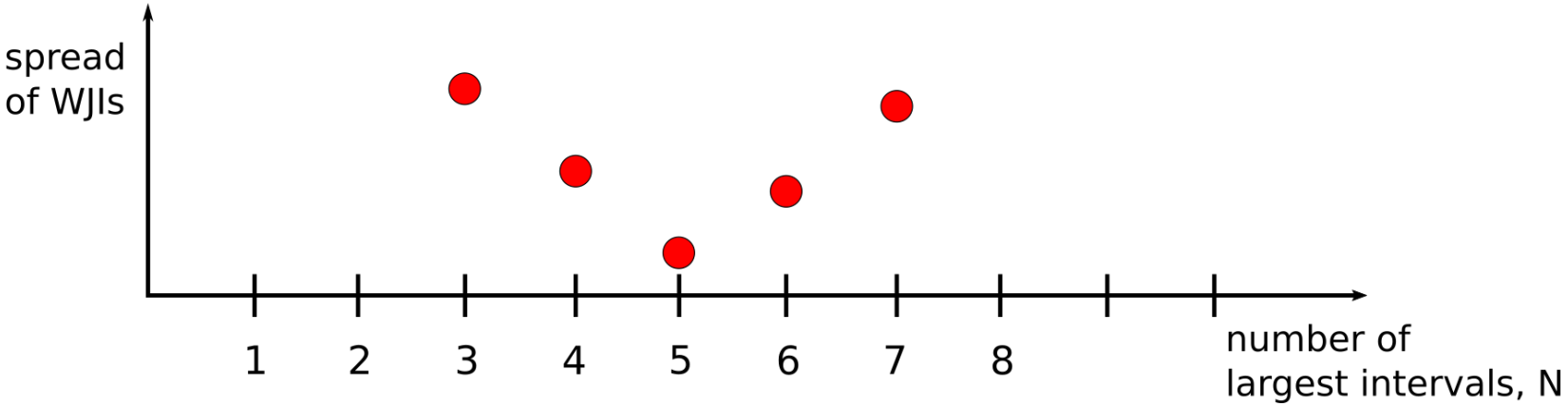

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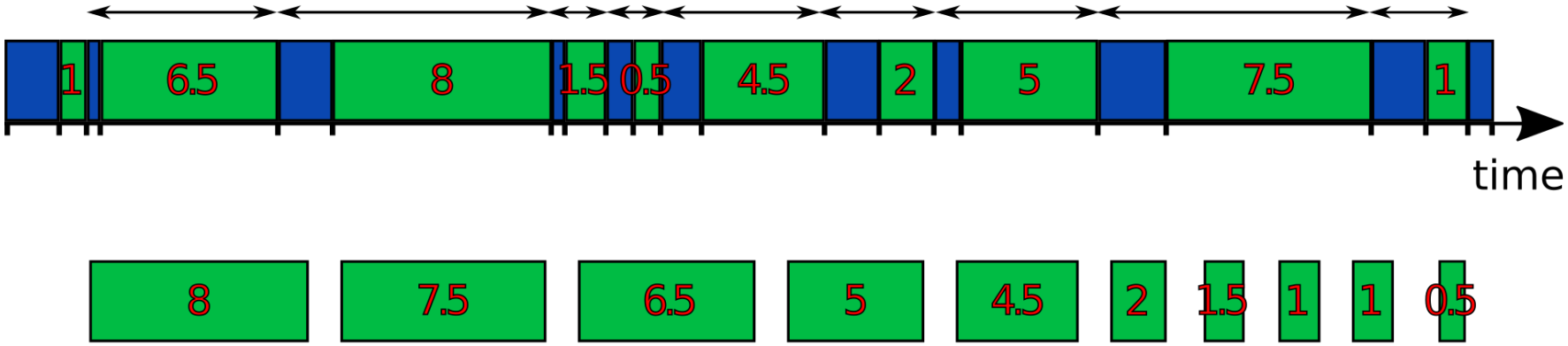

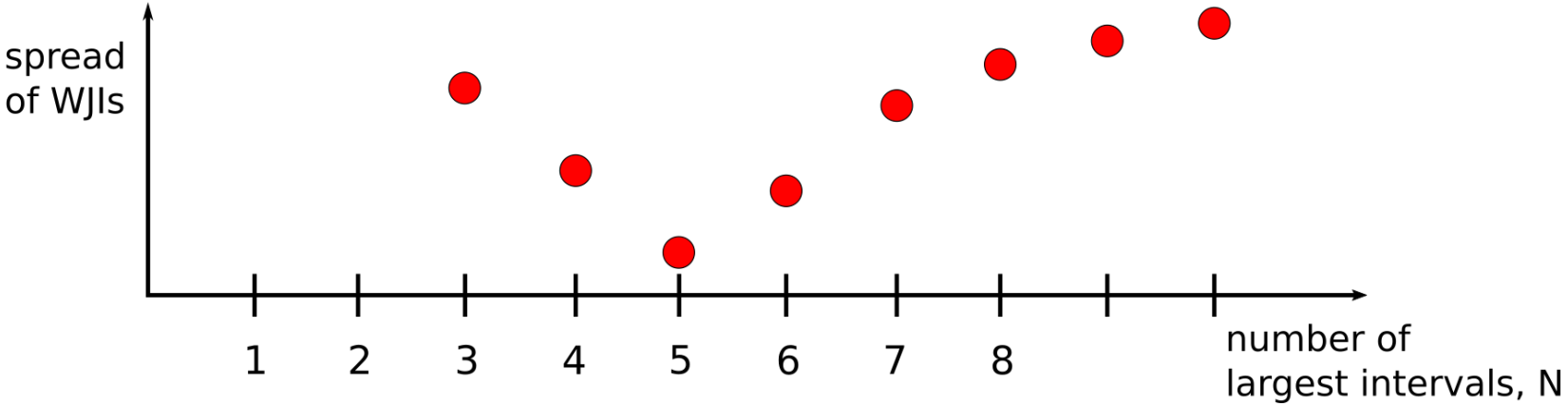

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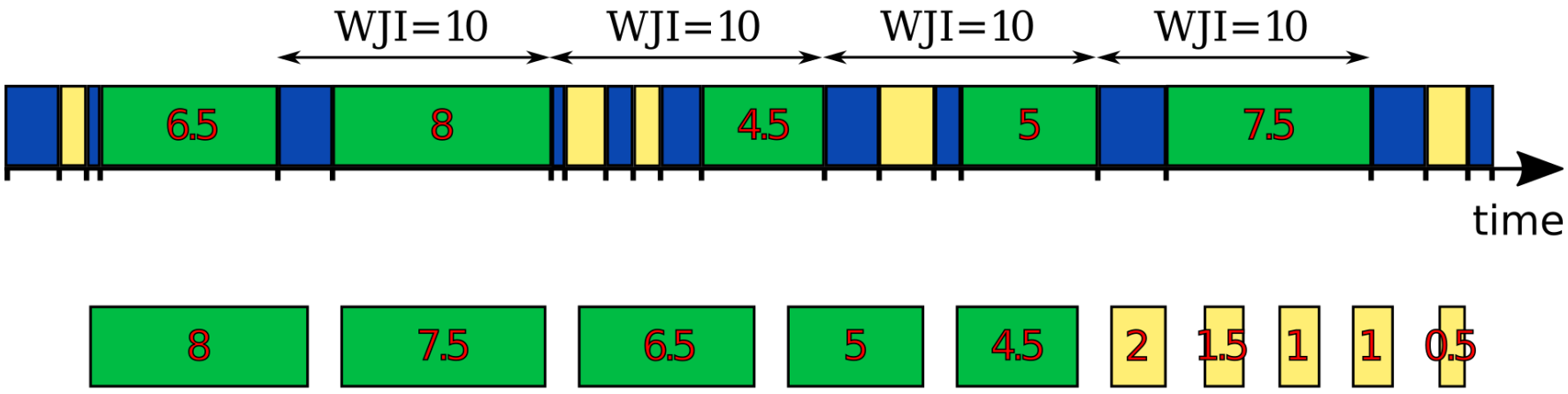
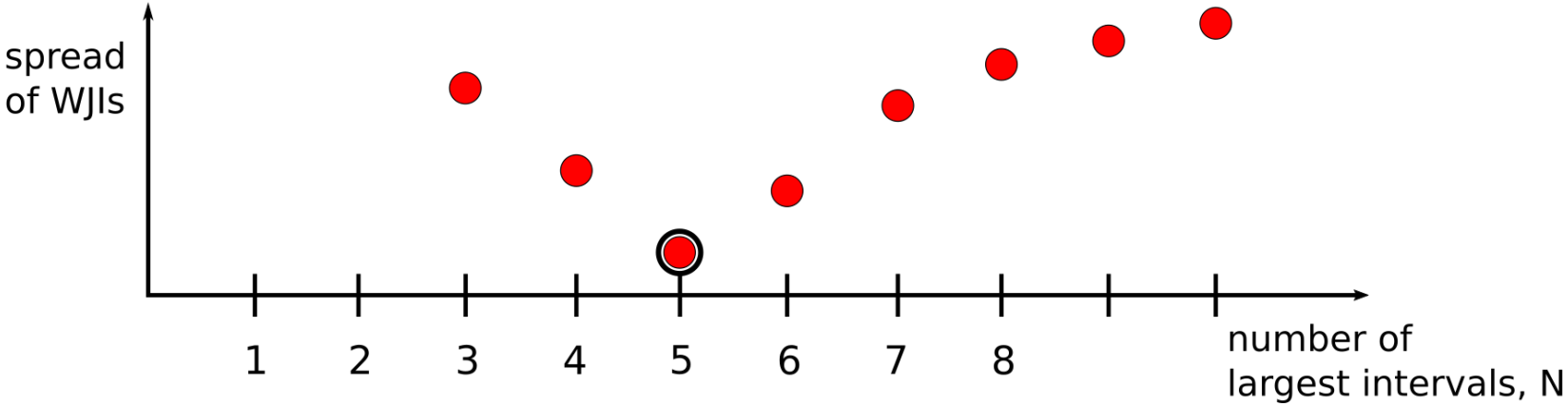
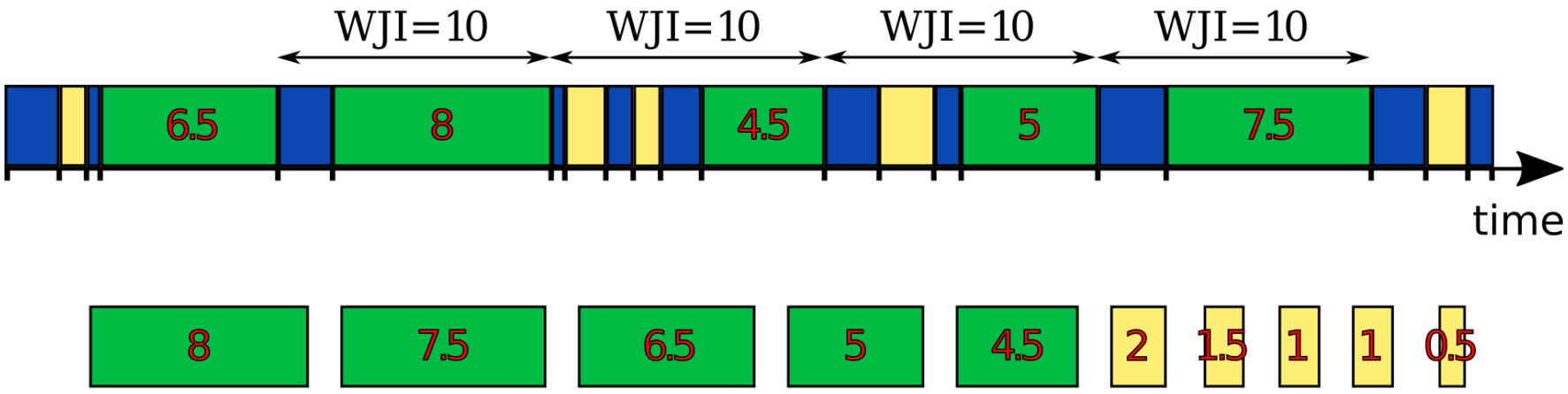
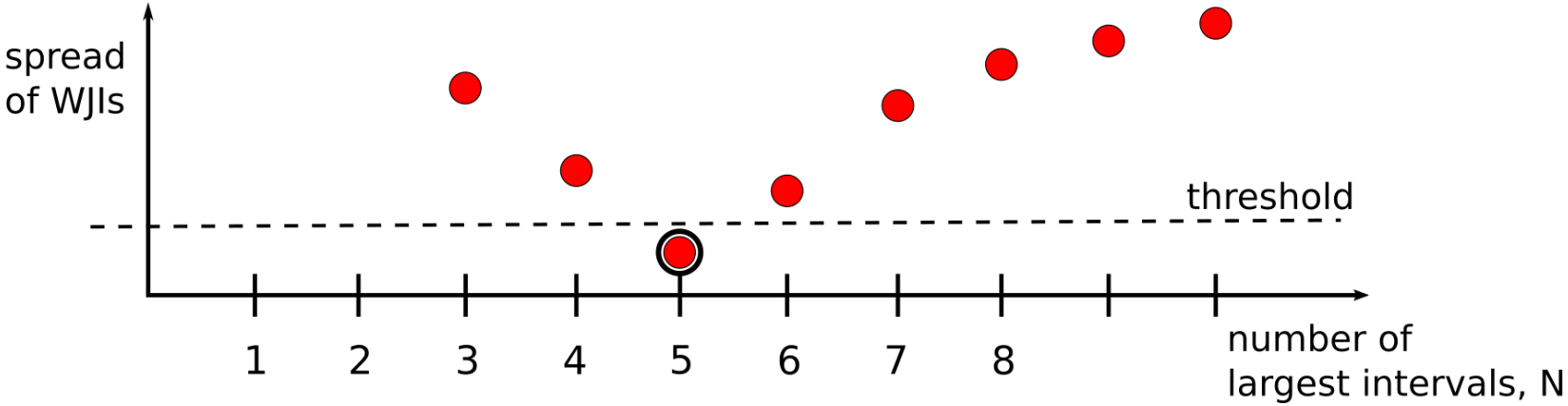




N largest intervals with the smallest spread of corresponding WJIs $\approx \{BJIs\}$

Mining Periodic Tasks from RTES Traces

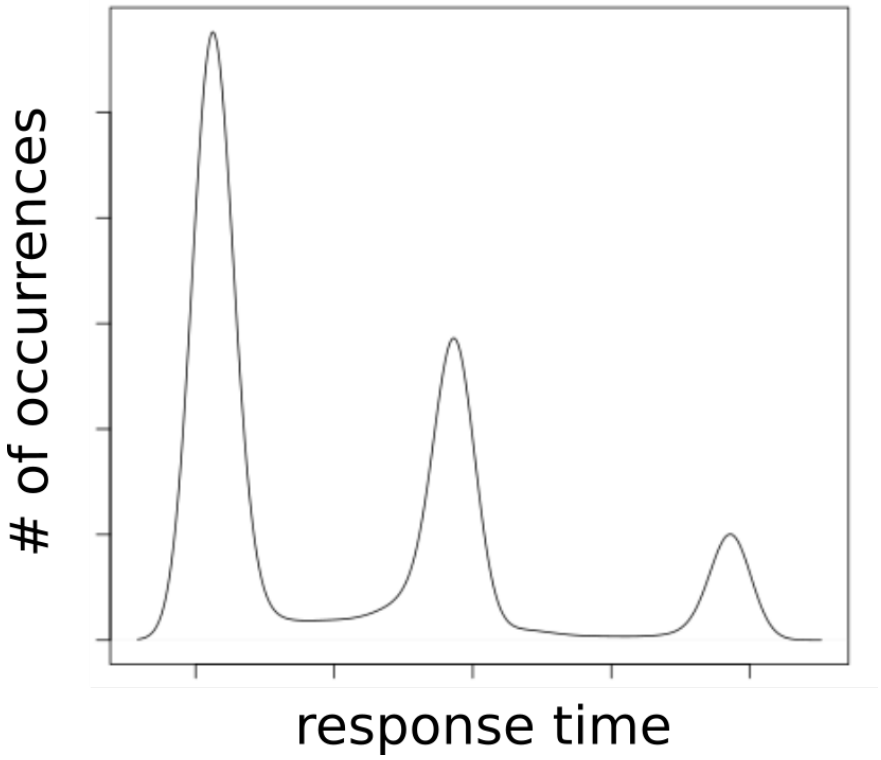




if $\texttt{spread}(\text{WJIs}) < \text{threshold}$, then task is periodic;
period $P = \texttt{mode}(\{\text{WJIs}\})$

Mining Response Time Profiles

$\{\text{response times}\} = P - \{BJIs\}$



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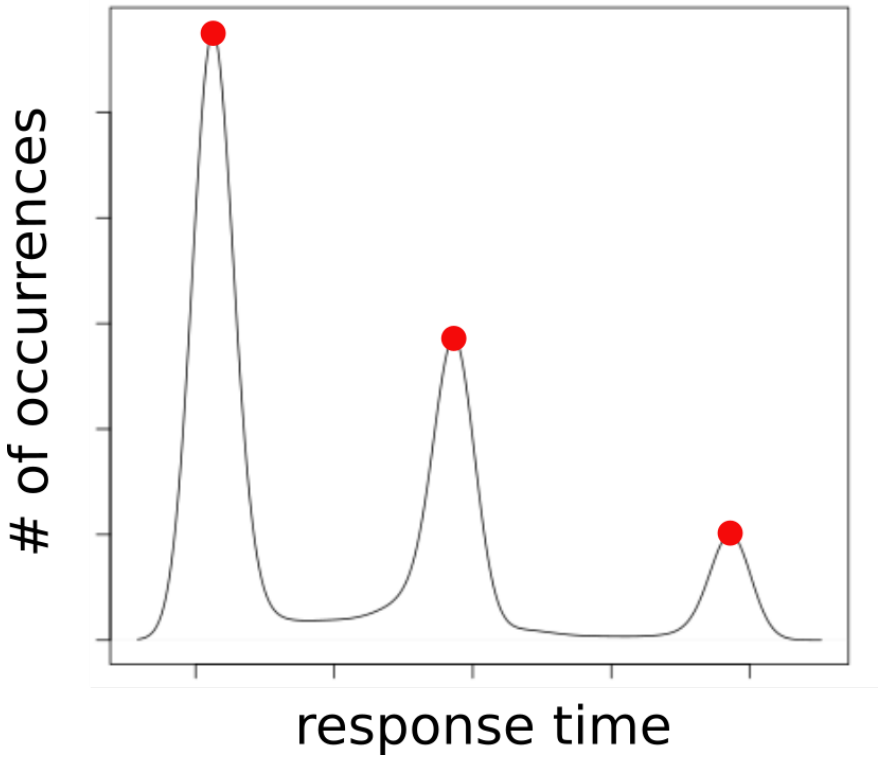
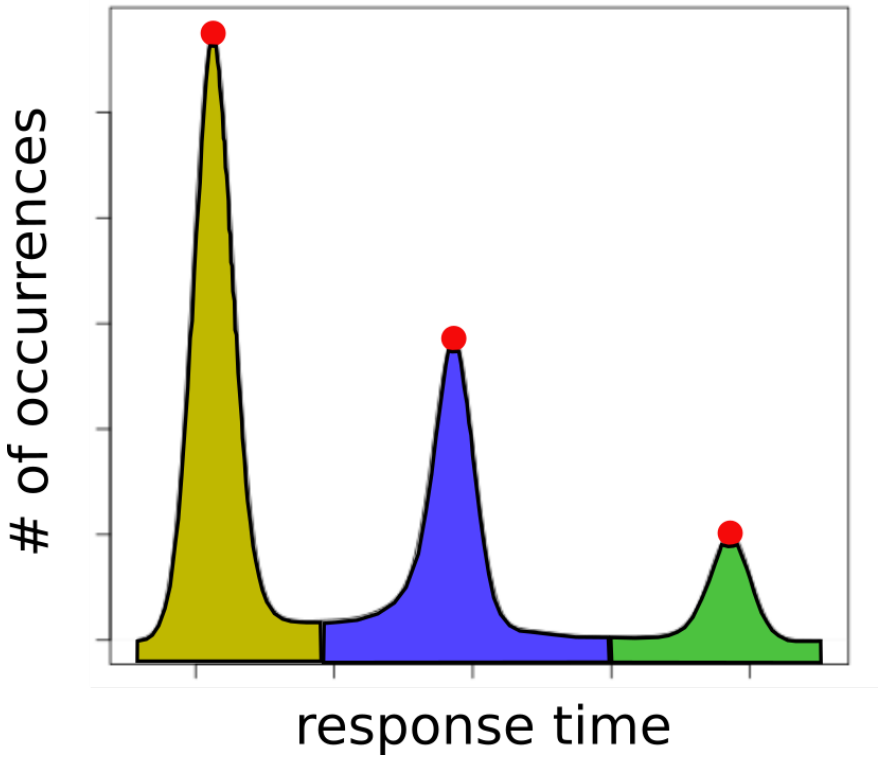


Mining of the most common response times.

Mining Response Time Profiles

$\{\text{response times}\} = P - \{BJIs\}$



Mining of the most common response times.

Clustering problem: the gap statistic and k-medoids clustering.

Case Studies

1. Unmanned Aerial Vehicle:
   - QNX Neutrino 6.4 RTOS;
   - 8 execution traces: ∼150K trace entries, 10 tasks;
   - accuracy of periodic task mining: 100%;
   - accuracy of RTP mining: 83%;

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   - accuracy of periodic task mining: 100%;
   - accuracy of RTP mining: 83%;

2. Toyota RAV4:
   - traces of Controller Area Network (CAN) messages;
   - 11 driving scenarios (starting the engine, lane changes, etc.);
   - ∼10K trace entries, 10-15 tasks per trace;
   - accuracy of periodic task mining: 100%;

Conclusion

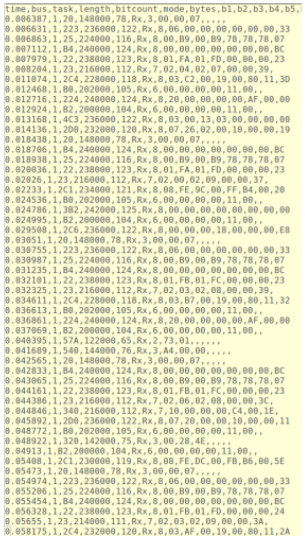
PeTaMi reverse engineering tool:

- mines periodic tasks and their response time profiles from RTES execution traces;
- relies on the assumption that in safe systems the slack between task's jobs is on average larger than job's individual preemption times;
- achieves good accuracy on traces of industrial RTES.

Real-Time Embedded System

execution →

Trace



```
time,bus,task,length,bitcount,mode,bytes,b1,b2,b3,b4,b5,
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0.006863,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.007112,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
0.007979,1,22,238000,123,Rx,8,01,FA,01,FD,00,00,00,23
0.008204,1,23,216000,112,Rx,7,02,04,02,07,00,00,39,
0.011074,1,2C4,228000,118,Rx,8,03,C2,00,19,00,80,11,3D
0.012468,1,B0,202000,105,Rx,6,00,00,00,00,11,00,,
0.012716,1,224,240000,124,Rx,8,20,00,00,00,00,AF,00,00
0.012924,1,B2,200000,104,Rx,6,00,00,00,00,11,00,,
0.013168,1,4C3,236000,122,Rx,8,03,00,13,03,00,00,00,00
0.014136,1,2D0,232000,120,Rx,8,07,26,02,00,10,00,00,19
0.018438,1,20,148000,78,Rx,3,00,00,07,,,,,
0.018706,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
0.018938,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.020036,1,22,238000,123,Rx,8,01,FA,01,FD,00,00,00,23
0.02026,1,23,216000,112,Rx,7,02,00,02,09,00,00,37,
0.02233,1,2C1,234000,121,Rx,8,08,FE,9C,00,FF,B4,00,20
0.024536,1,B0,202000,105,Rx,6,00,00,00,00,11,00,,
0.024786,1,3B2,242000,125,Rx,8,00,00,00,00,00,00,00,00
0.024995,1,B2,200000,104,Rx,6,00,00,00,00,11,00,,
0.029508,1,2C6,236000,122,Rx,8,00,00,00,18,00,00,00,E8
0.03051,1,20,148000,78,Rx,3,00,00,07,,,,,
0.030755,1,223,236000,122,Rx,8,06,00,00,00,00,00,00,33
0.030987,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.031235,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
0.032101,1,22,238000,123,Rx,8,01,FB,01,FC,00,00,00,23
0.032325,1,23,216000,112,Rx,7,02,03,02,08,00,00,39,
0.034611,1,2C4,228000,118,Rx,8,03,B7,00,19,00,80,11,32
0.036613,1,B0,202000,105,Rx,6,00,00,00,00,11,00,,
0.036861,1,224,240000,124,Rx,8,20,00,00,00,00,AF,00,00
0.037069,1,B2,200000,104,Rx,6,00,00,00,00,11,00,,
0.040395,1,57A,122000,65,Rx,2,73,01,,,,,,
0.041689,1,540,144000,76,Rx,3,A4,00,00,,,,,
0.042565,1,20,148000,78,Rx,3,00,00,07,,,,,
0.042833,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
0.043065,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.044161,1,22,238000,123,Rx,8,01,FB,01,FC,00,00,00,23
0.044386,1,23,216000,112,Rx,7,02,06,02,08,00,00,3C,
0.044846,1,340,216000,112,Rx,7,10,00,00,00,C4,00,1E,
0.045892,1,2D0,236000,122,Rx,8,07,20,00,00,10,00,00,11
0.048772,1,B0,202000,105,Rx,6,00,00,00,00,11,00,,
0.048922,1,320,142000,75,Rx,3,00,28,4E,,,,,
0.04913,1,B2,200000,104,Rx,6,00,00,00,00,11,00,,
0.05408,1,2C1,230000,119,Rx,8,08,FE,DC,00,FB,B6,00,5E
0.05473,1,20,148000,78,Rx,3,00,00,07,,,,,
0.054974,1,223,236000,122,Rx,8,06,00,00,00,00,00,00,33
0.055206,1,25,224000,116,Rx,8,00,B9,00,B9,78,78,78,07
0.055454,1,B4,240000,124,Rx,8,00,00,00,00,00,00,00,BC
0.056328,1,22,238000,123,Rx,8,01,FB,01,FD,00,00,00,24
0.05655,1,23,214000,111,Rx,7,02,03,02,09,00,00,3A,
0.058175,1,2C4,232000,120,Rx,8,03,AF,00,19,00,80,11,2A
```


PeTaMi →

Periodic tasks

- task_5D3: T=4ms, RTP=[1.3ms, 0.8ms]
- task_37A: T=12ms, RTP=[5ms]
- task_1Z1: T=8ms, RTP=[2ms, 0.4ms, 1.5ms]

...

Slack time analysis