7.a WCET analysis techniques

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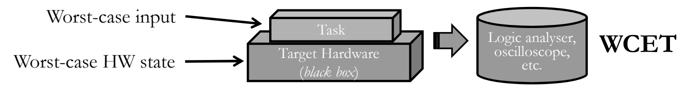
Worst-case execution time (WCET)

- For any input data and all initial logical states
  - So that all execution paths are covered
- For any hardware state
  - So that worst-case execution conditions are in effect
- Measurement-based WCET analysis
  - On the real HW or a cycle-accurate simulator
  - The *high-watermark* value can be ≤ WCET
- Static WCET analysis
  - On an abstract model of the HW and of the program

Computing the WCET /1

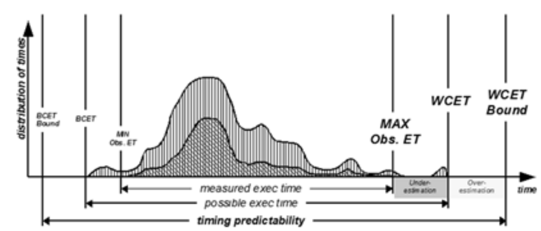
- Why not measure the WCET of a task on its real hardware?



- Triggering the WCET by test is very difficult
  - Worst-case input covering all executions of a real program is intractable in practice
  - Worst-case initial state is difficult to determine with modern HW
    - Complex pipelines (out-of-order execution)
    - Caches
    - Branch predictors and speculative execution

Computing the WCET /2

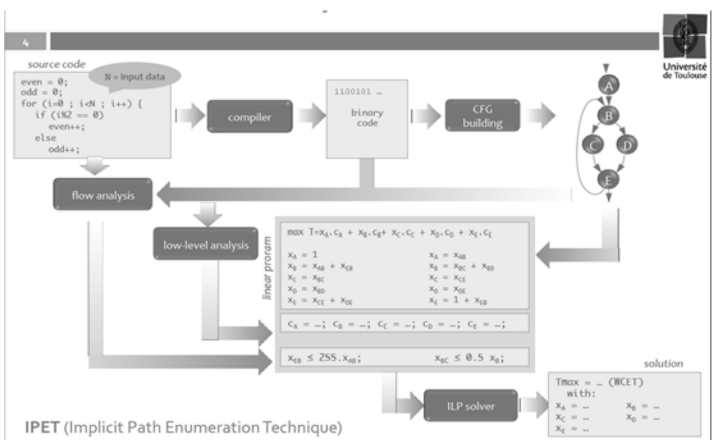
- Exact WCET not generally computable (~ the *halting problem*)
- A WCET estimate or *bound* are key to predictability
  - Must be *safe* to be an upper bound to all possible executions
  - Must be *tight* to avoid costly over-dimensioning



Static WCET analysis /1

- To analyze a program without executing it
  - Needs an *abstract model* of the target HW
  - As well as the actual executable
- Execution time depends on control path and HW
  - *High-level analysis* addresses the program behavior
    - Control flow analysis builds a control flow graph (CFG)
  - *Low-level analysis* determines the timing behavior of individual instructions
    - Not constant for modern HW
    - Must be aware of the HW inner workings (pipeline, caches, etc.)

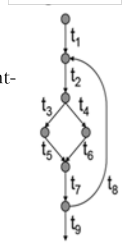
Static WCET analysis /2



Implicit path enumeration technique

- The program structure is mapped into flow graph constraints
  - WCET computed with integer linear programming or constraint-solving techniques
- $WCET = \sum_i x_i \times t_i$
  - Where x_i is the execution frequency of CFG edge i
  - And t_i the execution time of CFG edge i

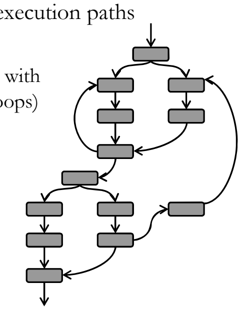
CFG



Flow constraints
x1 = 1
x1 + x8 = x2
x2 = x3 + x4
x3 = x5
x4 = x6
x5 + x6 = x7
x7 = x8 + x9
x2 <= LB * x1

Static WCET analysis /3

- ***High-level analysis*** /1
  - Must analyze all possible execution paths of the program
    - Builds the CFG as a superset of all possible execution paths
    - *Basic block* is the unit of that analysis
      - The longest sequence of program instructions with single entry and single exit (no branches, no loops)
  - Challenges with path analysis
    - *Input-data dependency*
    - *Infeasible paths*
    - *Loop bounds* (and recursion depth)
    - *Dynamic calls* (through pointers)



Static WCET analysis /4

- ***High-level analysis*** /2
  - Several techniques are deployed to allow using IPET
    - *Control-flow analysis* to construct the CFG
      - First finding the basic blocks and then building the graph among them
    - *Data-flow analysis* to find loop bounds
    - *Value analysis* to resolve memory accesses
  - Automatic information extraction is insufficient 
    - User annotation of *flow facts* is needed
      - To facilitate detection of infeasible paths
      - To refine loop bounds
      - To define frequency relations between basic blocks
      - To specify the target of dynamic calls and referenced memory addresses

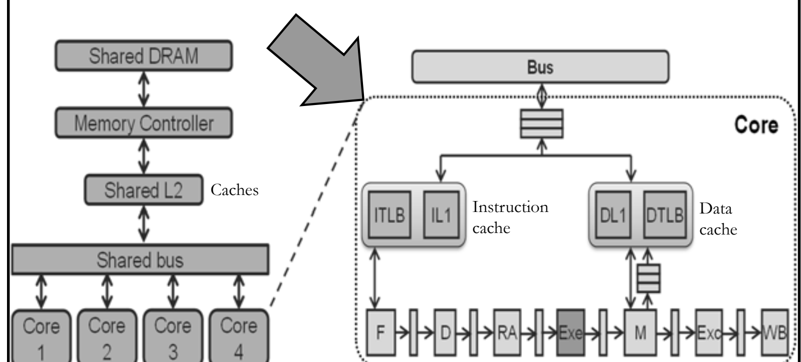
Static WCET analysis /5

- ***Low-level analysis*** /1
  - Requires abstract modeling of all HW features
    - Processor, memory subsystem, buses, peripherals, …
    - It is *conservative* : it must never underestimate actual timing
    - All possible HW states should be accounted for
  - Challenges with HW modeling
    - *Precise modeling* of complex hardware is difficult
      - Inherent complexity (e.g., out-of-order pipelines)
      - Lack of comprehensive information (intellectual property, patents, …)
      - Differences between specification and implementation (!)
    - *Exhaustive representation* of all HW states is computationally infeasible

Static WCET analysis /6

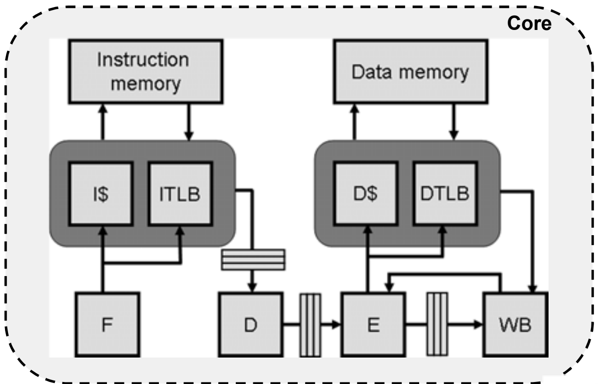
- ***Low-level analysis*** /2
  - Concrete HW states
    - Determined by the history of execution
    - Cannot compute all HW states for all possible executions
      - Invariant HW states are grouped into execution contexts
      - *Conservative overestimations* are made to reduce the research space
  - *Abstract interpretation*
    - Computes abstract states and specific operators in the abstract domain
      - *Update function* to keep the abstract state current along the exec path
      - *Join function* to merge control flows after a branch
  - Some techniques are specific to each HW feature

Understanding the hardware /1



Courtesy of PROXIMA

Understanding the hardware /2



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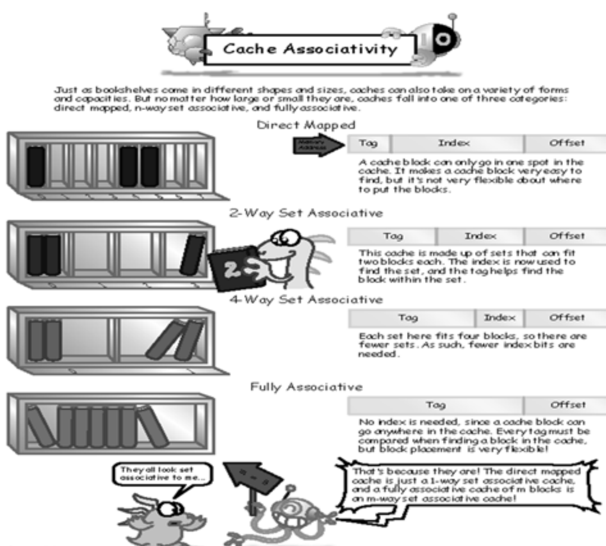
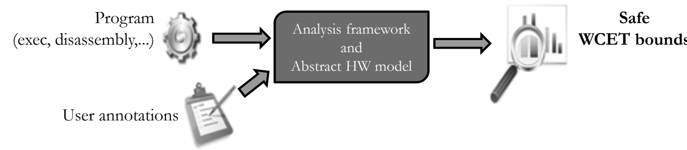


Static WCET analysis: the big picture



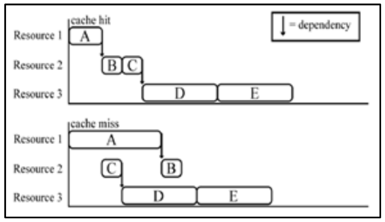
- Open problems
  - Can we always trust HW modeling?
  - How much overestimation do we incur?
    - Inclusion of infeasible paths
    - Overestimation intrinsic in abstract state computation
  - Weaknesses of user annotations
    - Labor intensive and error prone

Static WCET analysis /7

- Safeness is at risk
  - When *local* worst case does not always lead to *global* worst case
  - When *timing anomalies* occur
    - Complex hardware architectures (e.g., out-of-order pipelines)
    - Even improper design choices (e.g., cache replacement policies)
    - *Counter-intuitive* timing behavior
    - Faster execution of a single instruction causes *long-term* negative effects
  - Both are very difficult to account for in static analysis

Scheduling anomaly: example

- Some dependence between instructions
- Shared resources (e.g. pipeline stages) and opportunistic scheduling



- Faster execution of A leads to a worse case overall execution because of the order in which instructions are executed

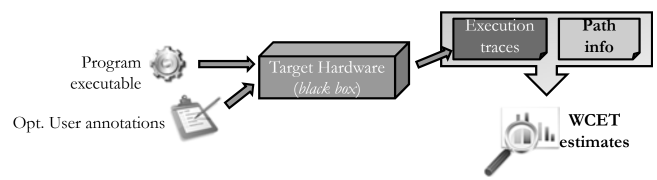
Hybrid analysis /1

- To obtain *realistic* (less pessimistic) WCET estimates
  - On the real target processor
  - On the final executable
  - Knowing that safeness not guaranteed (**!**)
- Hybrid approaches exploit
  - The measurement of *basic blocks* on the real HW
    - To avoid pessimism from abstract modeling
  - Static analysis techniques to combine the obtained measures
    - Knowledge of the program execution paths
- Newer approaches explore probabilistic properties (**!**)

Hybrid analysis /2

- Approaches to collect timing information
  - *Software instrumentation*
    - The program is augmented with instrumentation code
    - Instrumentation effects the timing behavior of the program (aka the *probe effect*) and causes problems to deciding what's the final system
  - *Hardware instrumentation*
    - Depends on specialized HW features (e.g., debug interface)
- Confidence in the results contingent on the coverage of the executions and on the exploration of worst-case states
  - Exposed to the same problems as static analysis and measurement
  - *Worst-case state dependence is gone if HW response time is randomized*

Hybrid analysis: the big picture



- Open problems
  - Can we trust the resulting estimates?
    - Contingent on worst-case input and worst-case HW state
    - Consideration of infeasible paths
  - Needs the real execution environment or an identical copy of it
    - May cause serious cost impact and inherent difficulty of exactness

Summary

- The challenge of computing the WCET
- Static analysis
  - High-level analysis
  - Low-level analysis
- Hybrid analysis (measurement-based)

7.b Schedulability analysis techniques

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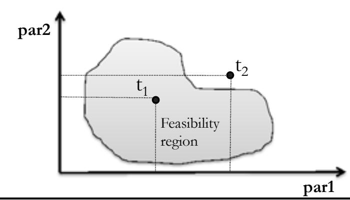
Selected readings

- R. Wilhelm et al. (**2008**)
  The worst-case execution-time problem—overview of methods and survey of tools
  DOI: 10.1145/1347375.1347389

Feasibility region

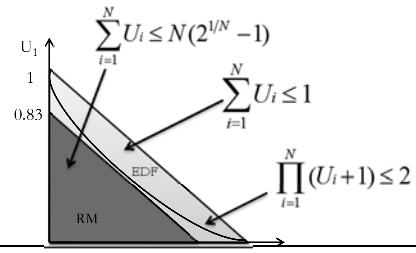
- The topological space that represents the set of feasible systems with respect to the workload model parameters
  - N-dimensional space with N-parameter analysis
  - Function of the timing parameters
  - Specific to the scheduling policy in force



t_1 is feasible
t_2 is not feasible

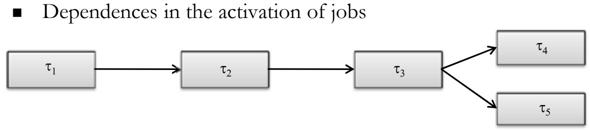
Advanced utilization tests

- *Hyperbolic bound* improves Liu & Layland utilization test
  - For systems with periodic tasks under FPS and DMPO
  - E. Bini and G. Buttazzo: "*A Hyperbolic Bound for the Rate Monotonic Algorithm*". Proceedings of the 13th ECRTS, 2001



Transactions /1

- Causal relations between activities
  - They consider information relevant to analysis that is not captured by classic workload models
    - Dependences in the activation of jobs

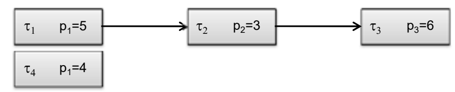


  - Originally introduced for the analysis of distributed systems
    - Also useful for the analysis of "collaboration patterns" employed for single-CPU systems

Transactions /2

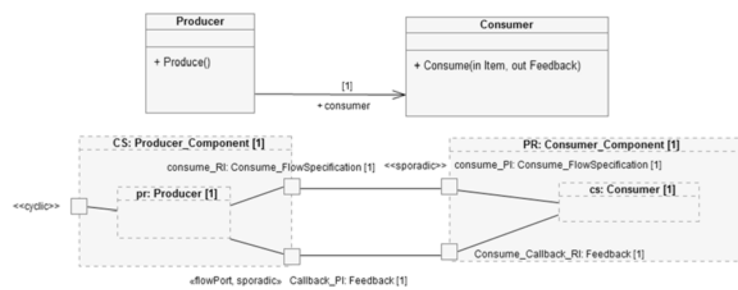
- Two main kinds of dependence
  - *Direct precedence* relation (e.g., producer-consumer)
    - τ_2 cannot proceed until τ_1 completes

  - *Indirect priority* relation
    - τ_4 does not suffer interference from τ_3 (under FPS and synchronous release of τ_1 and τ_4 for priorities increasing with values)

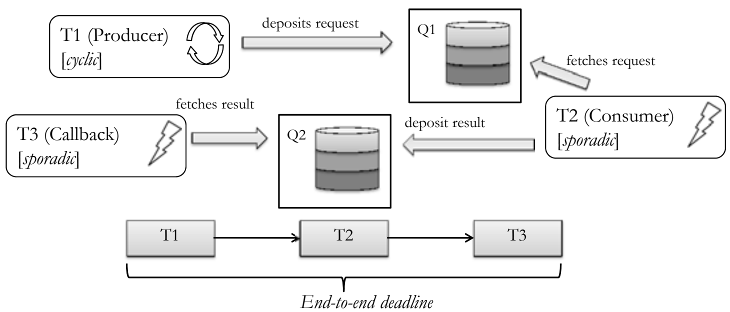


Example /1

- A "*callback pattern*" to permit **in out** interactions between tasks in Ravenscar systems



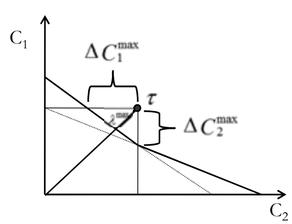
Example /2



The feasibility of the *end-to-end response time* against this deadline is what matters (!)

Sensitivity analysis /1

- Investigates the changes in a given system that
  - Improve the fit of an already feasible system
  - Make feasible an infeasible system



τ Position of the system in the feasibility region

ΔC_1^{max} Maximum feasible variation for the WCET of t_1 (negative in the example)

ΔC_2^{max} Maximum feasible variation for the WCET of t_2 (negative in the example)

Sensitivity analysis /2

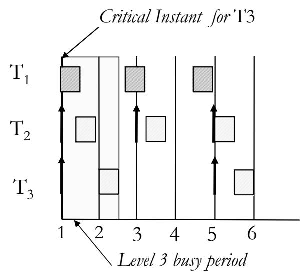
- Major computation complexity
- Theory still under development
  - Does not account for shared resources, multi-node systems, partitioned systems
- High potential
  - To explore solution space in the *dimensioning* phase of design
    - Presently only applicable to period/MIAT and WCET
  - To study the consequences of changes to timing parameters
    - To allow for the inclusion of better functional value in the system
    - To renegotiate timing (or functional) parameters

MAST

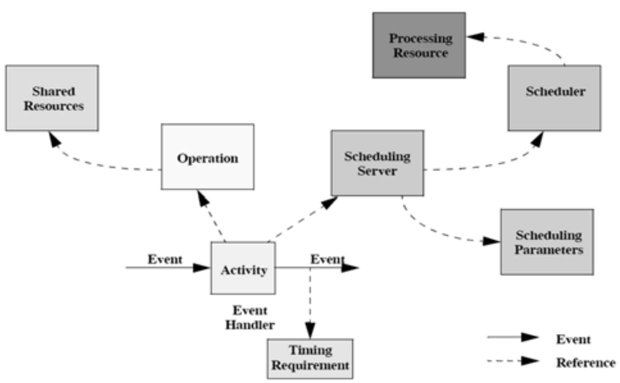
- Modeling and Analysis Suite for Real-Time Systems (MAST, http://mast.unican.es)
  - Developed at University of Cantabria, Spain
  - Open source
  - Implements several analysis techniques
    - For uniprocessor and distributed (no-shared memory) processor systems
    - Under FPS or EDF

Classic workload model

T_1	(Sporadic)	MIAT=1.750	WCET=0.500
T_2	(Cyclic)	T=2.000	WCET=0.500
T_3	(Cyclic)	T=4.000	WCET=0.500

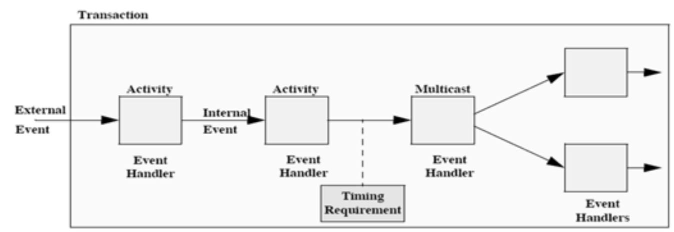


MAST: real-time model

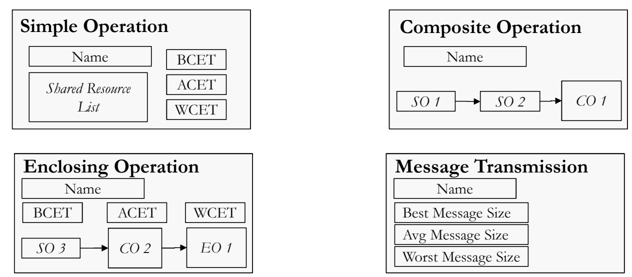


MAST: transaction

- To model causal relations between activities
  - Triggered by external events
    - Periodic, sporadic, aperiodic, etc…

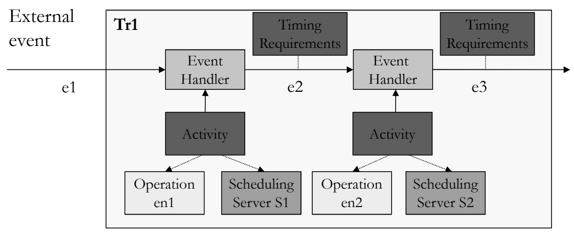


MAST: operations

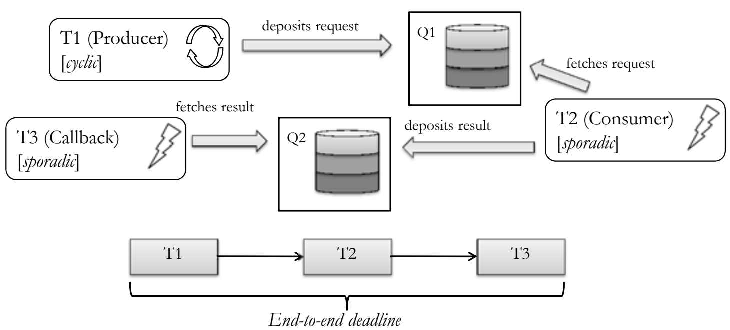


- The real-time model includes the description of all the operations in the system

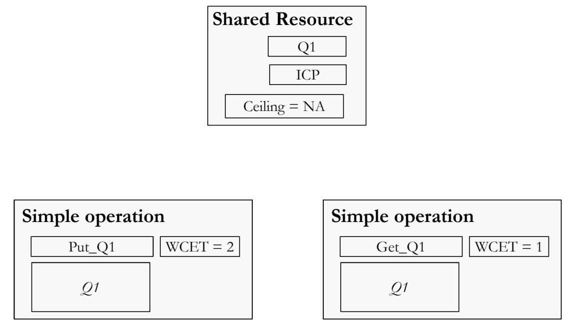
MAST: creation of a transaction



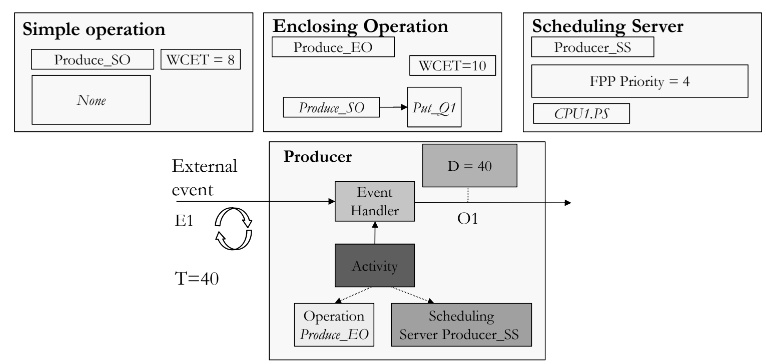
Example: Ravenscar callback



Example: shared resources in MAST



Example: modeling tasks in MAST



Example: timing attributes

Producer [1]	(C)	T_1=40	C_1=10	p_1=4
Consumer [2]	(S)	T_2=40	C_2=10	p_2=2
Callback [3]	(S)	T_3=40	C_3=5	p_3=5

Q1 Ceiling=4

Q2 Ceiling=5

Example: classic RTA results

Producer [1]	(C)	T_1=40	C_1=10	p_1=4
Consumer [2]	(S)	T_2=40	C_2=10	p_2=2
Callback [3]	(S)	T_3=40	C_3=5	p_3=5

Q1 Ceiling=4

Q2 Ceiling=5

⇒ B_1=2 B_2=0 B_3=2

Classic RTA

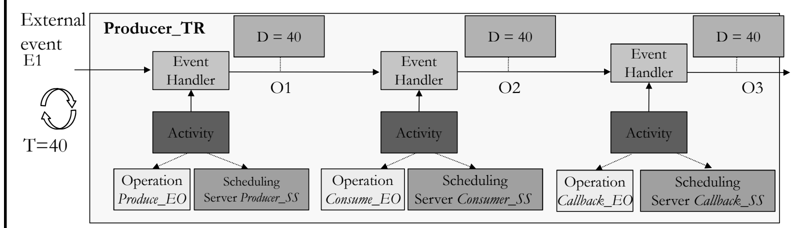
R_1 = 17

R_2 = 25

R_3 = 7

This misses out completely that T_3 is to be *preceded* by T_2 and T_1 (!)

Example: introducing transactions



Example: end-to-end analysis

Producer [1]	(C)	T_1=40	C_1=10	p_1=4
Consumer [2]	(S)	T_2=40	C_2=10	p_2=2
Callback [3]	(S)	T_3=40	C_3=5	p_3=5

Q1 Ceiling=4

Q2 Ceiling=5

⇒ B_1=2 B_2=0 B_3=2

Classic RTA	***Precedence and offset-based***
R_1 = 17	R_1 (Tr) = 12
R_2 = 25	R_2 (Tr) = 20
R_3 = 7	R_3 (Tr) = 27

⇐ ***Response time*** **relative to the beginning of the transaction!**

Summary

- Feasibility region
- Advanced utilization tests
- Fine-grained response time analysis
- Transactions
- Sensitivity analysis
- Example tool (MAST)