A Framework to Quantify the Overestimations of Static WCET Analysis

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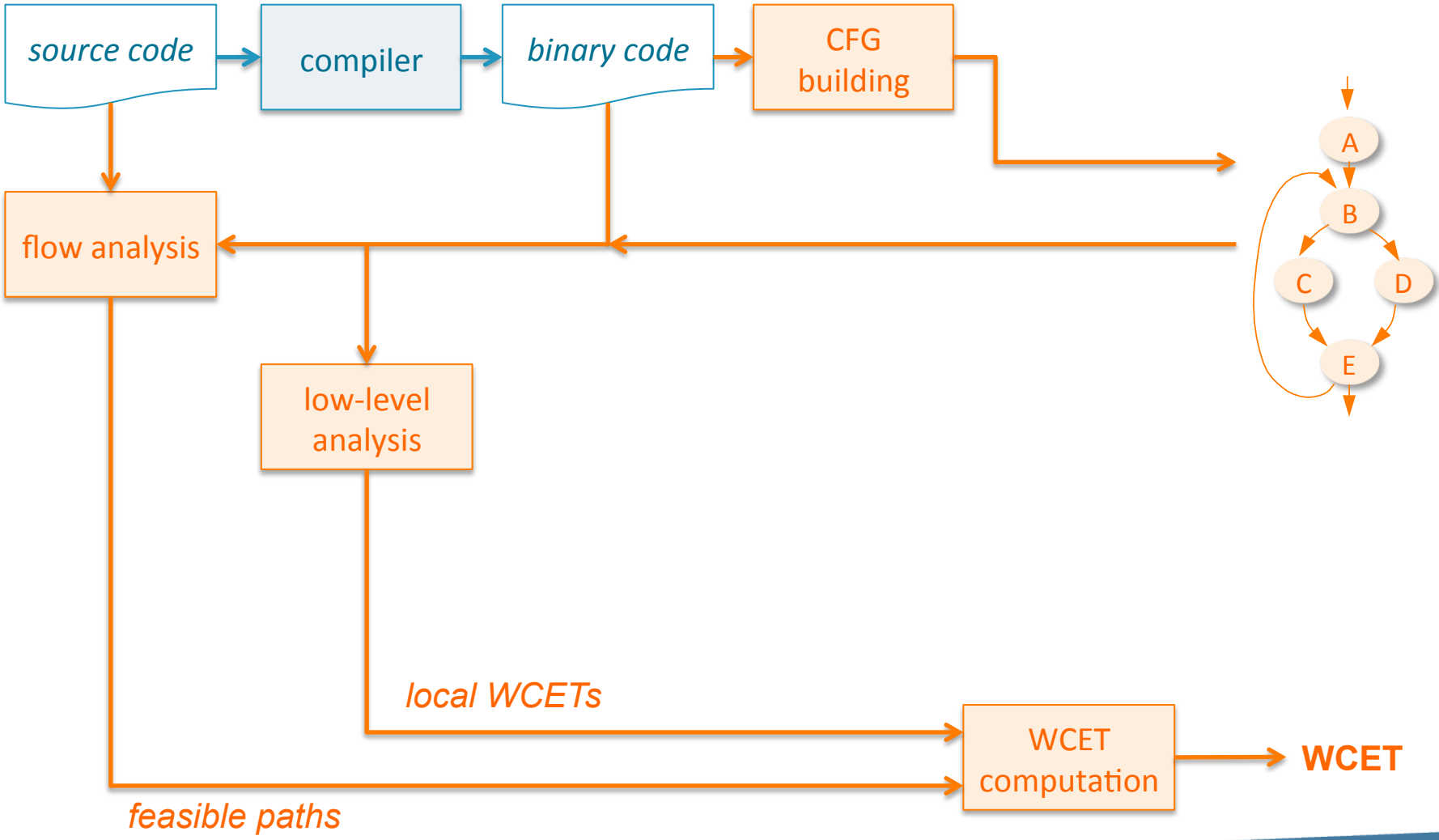
Static WCET analysis



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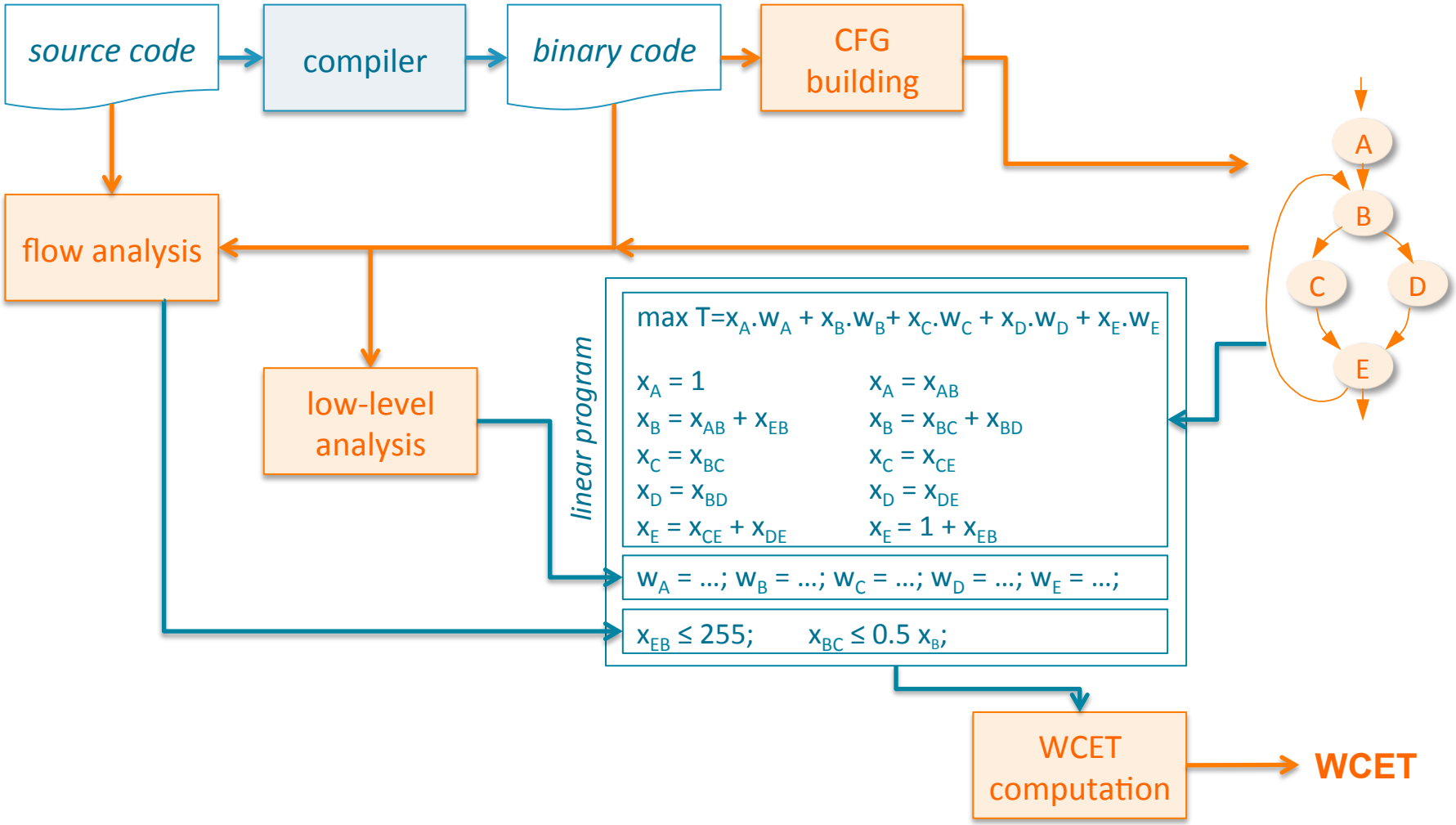
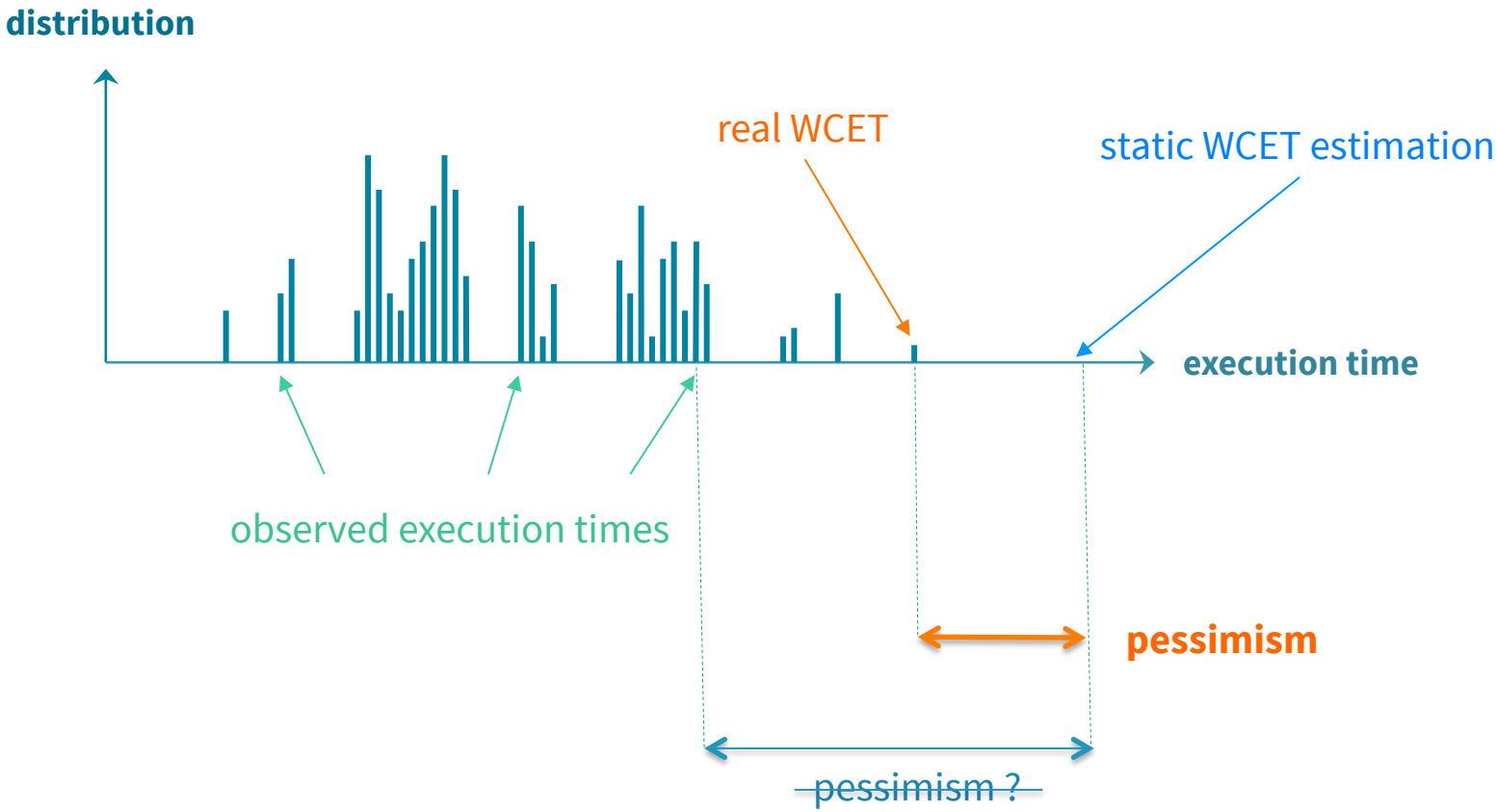


Implicit Path Enumeration Technique (IPET)

"Static analysis overestimates WCET"



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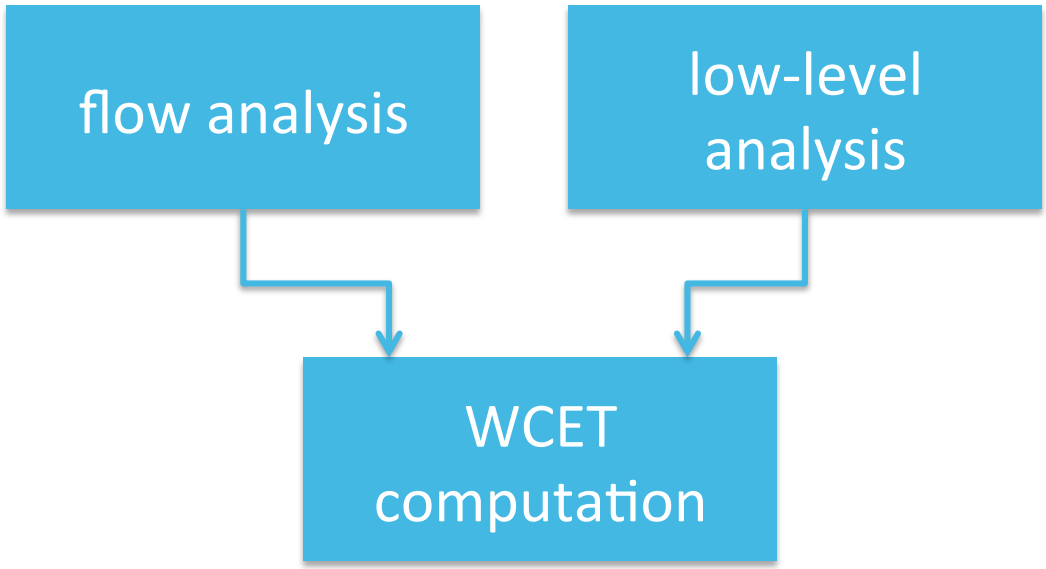

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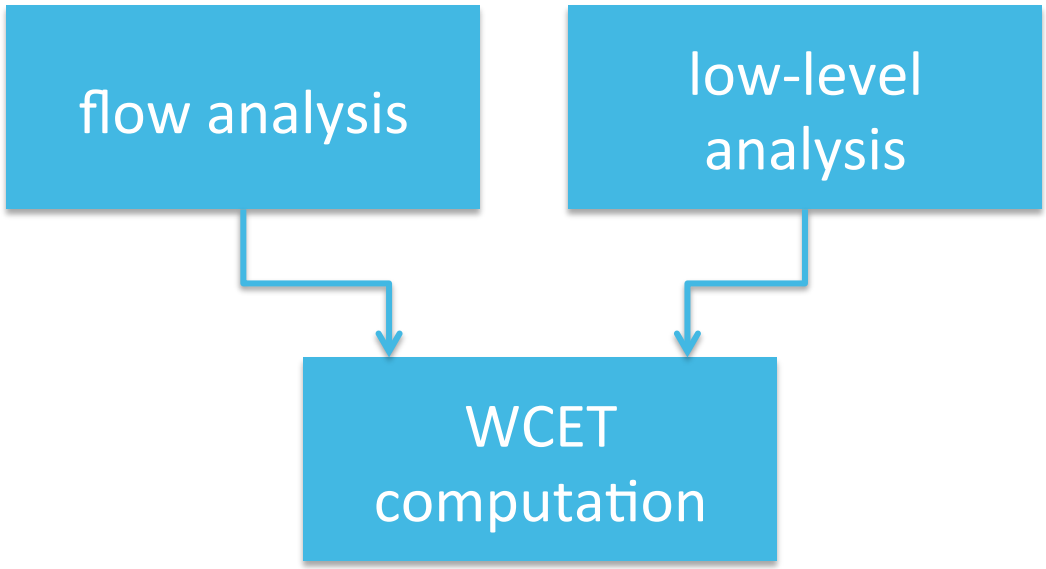

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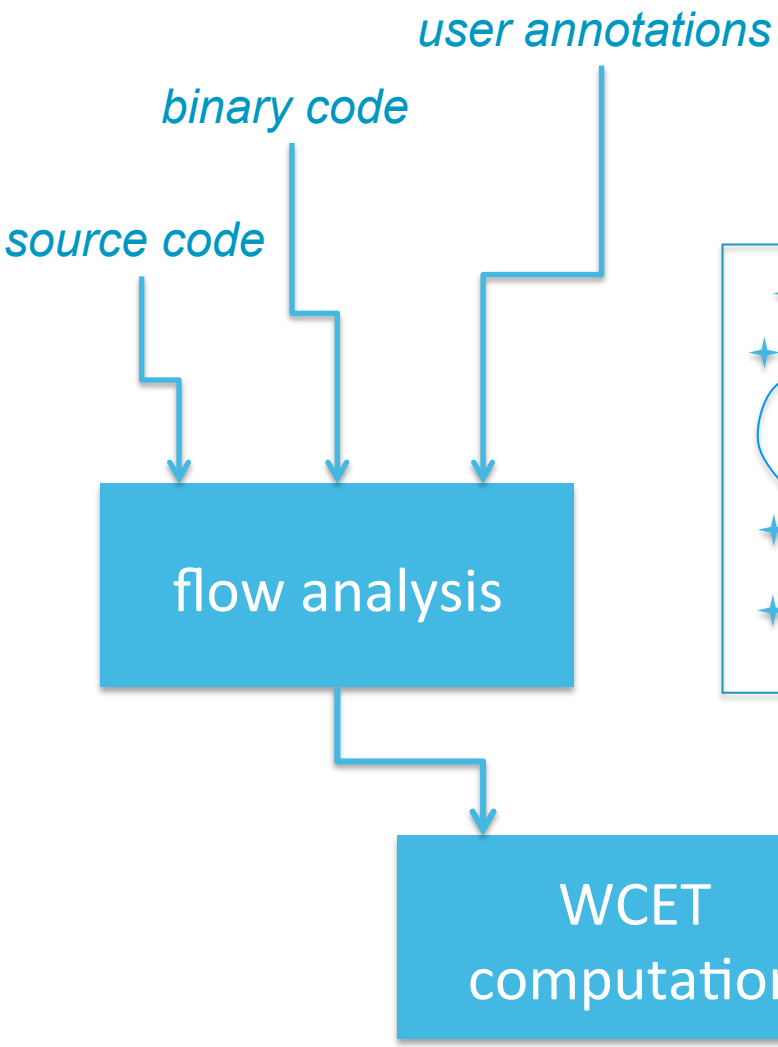
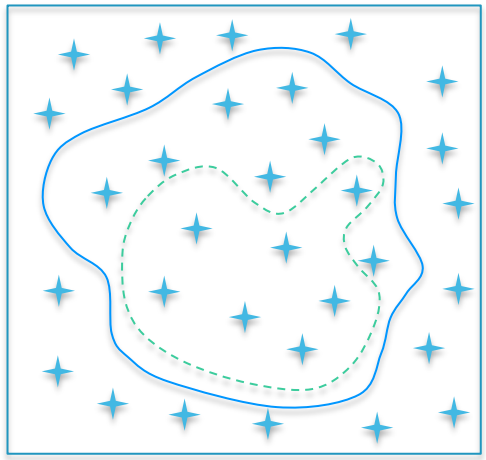
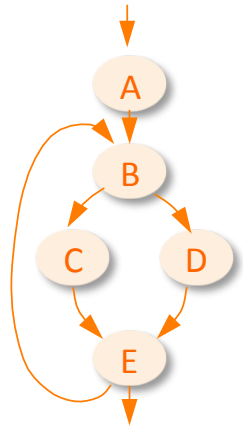






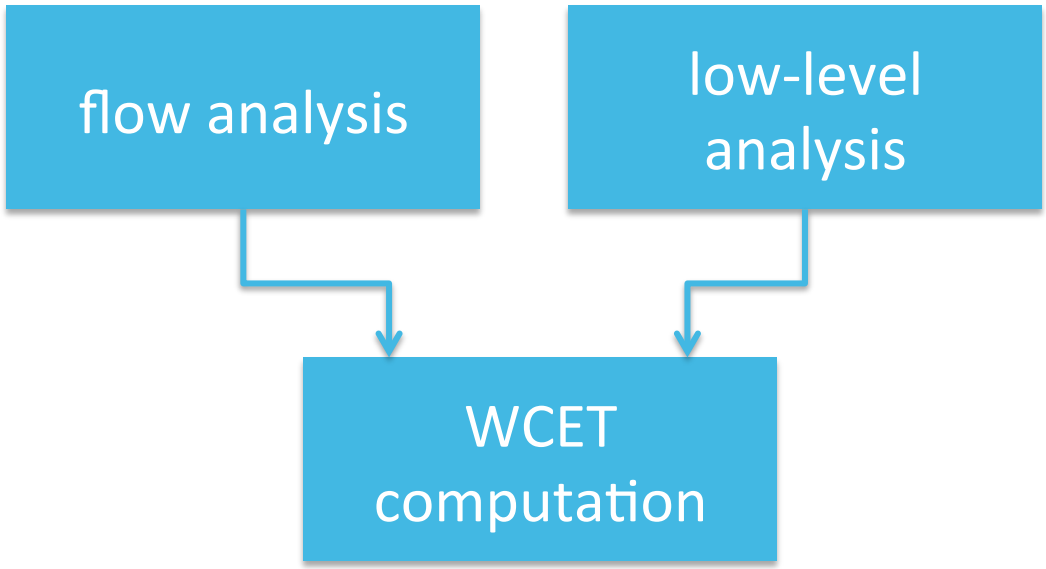
$\mathcal{P}^T$ = all the CFG paths

$\mathcal{P}^+ = \mathcal{P}^T$ – known-to-be-infeasible paths

$\mathcal{P}^r$ = really-feasible paths

longest paths

"Static analysis overestimates WCET"



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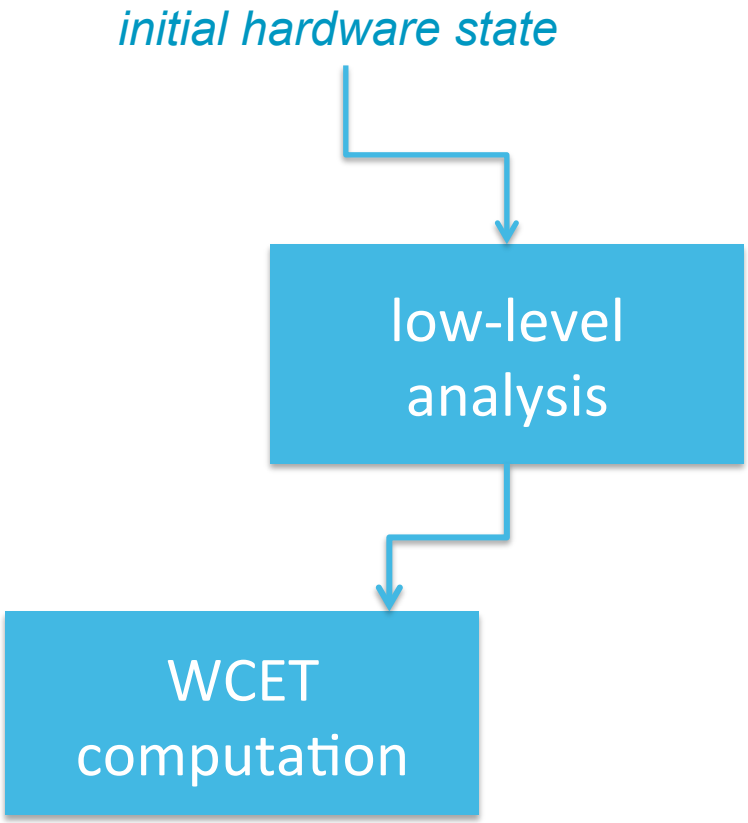

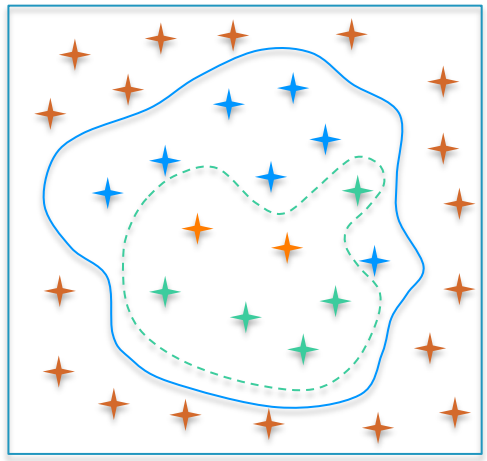

$\mathcal{H}^T$ = *all the theoretically-possible states*

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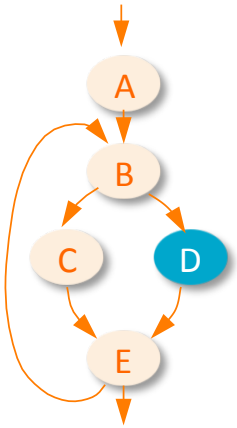
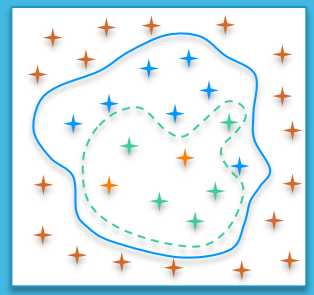
"Static analysis overestimates WCET"





low-level analysis

WCET computation

$\mathcal{C}^T$ = *all the theoretically-possible scenarios*

$\mathcal{C}^+$ = $\mathcal{C}^T$ – *known-to-be-infeasible scenarios*

$\mathcal{C}^r$ = *really-feasible scenarios*

Static analysis determines local WCETs (basic blocks)
- abstracts (over-approximates) hardware states
- considers all "maybe-possible" scenarios

Quantifying the pessimism of WCET estimates

Real WCET $\quad ET : \mathcal{H} \times \mathcal{P} \rightarrow \mathbb{N} \qquad WCET = \max_{(h,p) \in \mathcal{H} \times \mathcal{P}} ET(h,p)$

Static WCET estimation $\quad WCET^{\#} : \mathcal{H} \times \mathcal{P} \times \mathcal{C} \rightarrow \mathbb{N}$

- upper bound on the WCET:

$$WCET^{+} = \max_{(h,p,c) \in \mathcal{H}^{+} \times \mathcal{P}^{+} \times \mathcal{C}^{+}} ET(h,p,c)$$

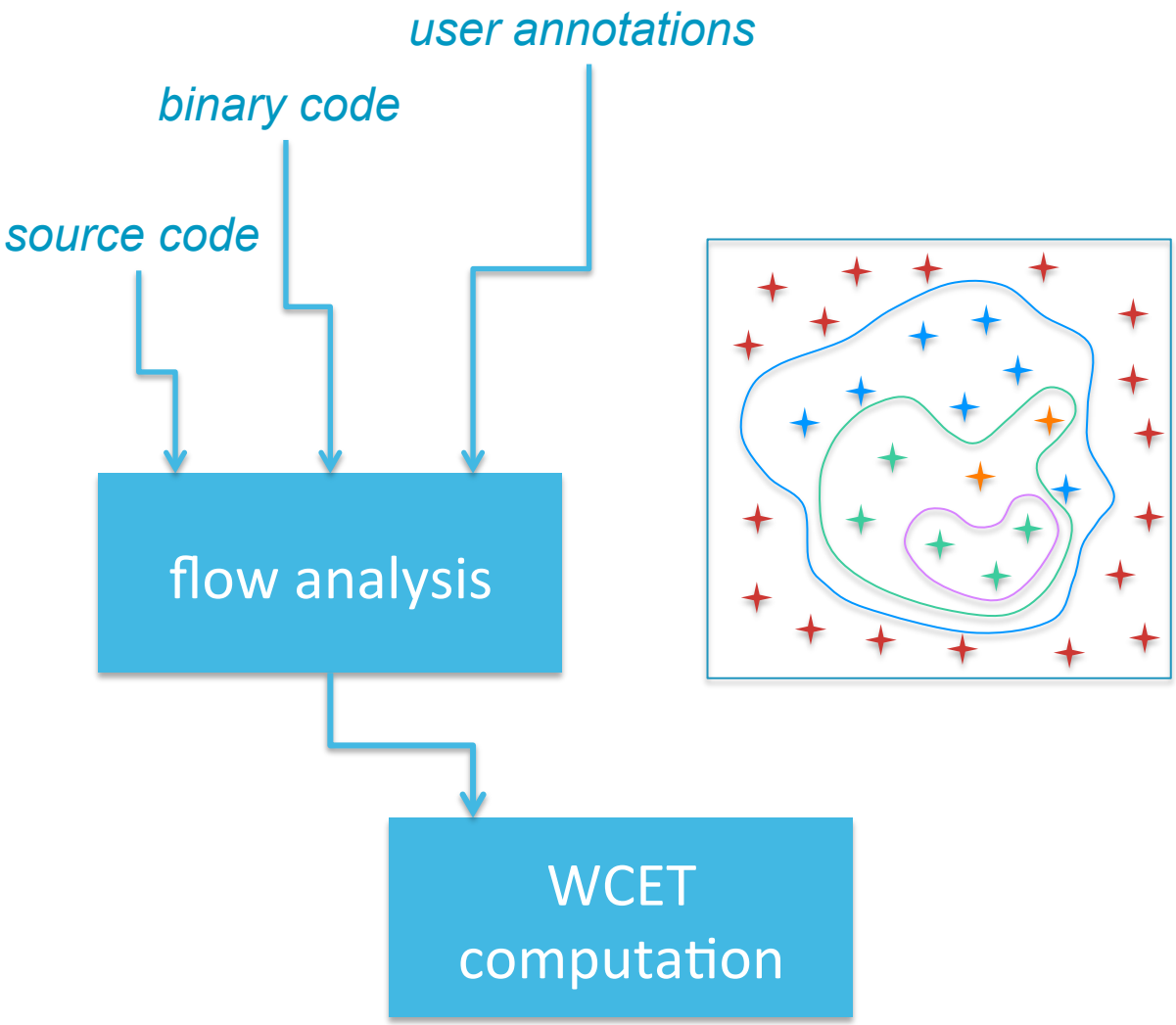
$$WCET^{r} \leq WCET^{+}$$

- **lower bound** on the WCET:

$$WCET^{-} \leq WCET^{r} \leq WCET^{+}$$

$U = WCET^{+} - WCET^{-}$

Quantifying the pessimism of WCET estimates



$\mathcal{P}^T$ = all the CFG paths

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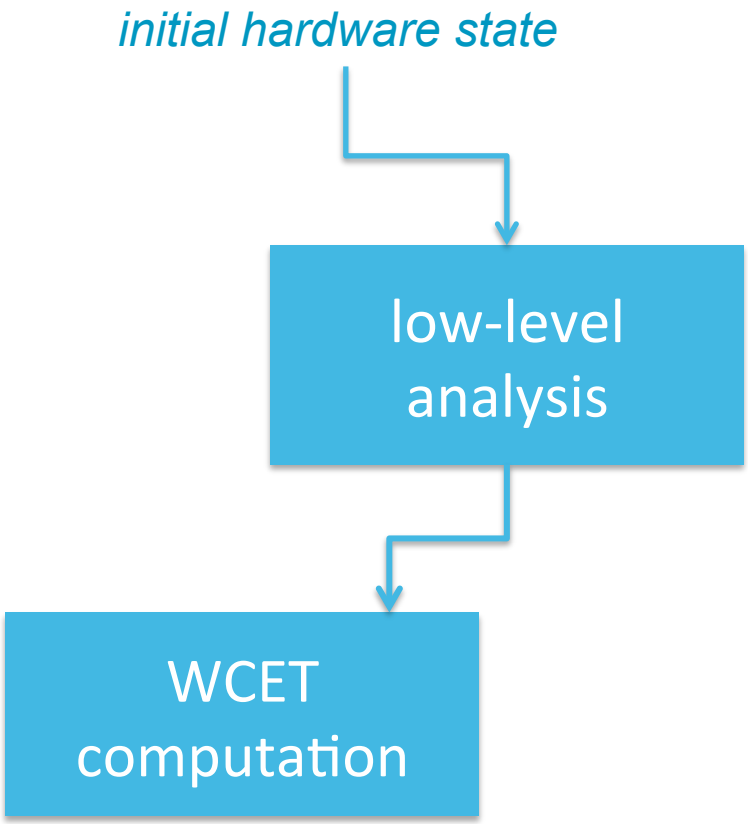
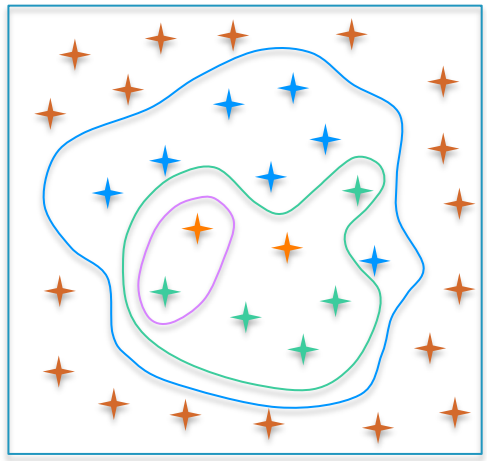
Quantifying the pessimism of WCET estimates





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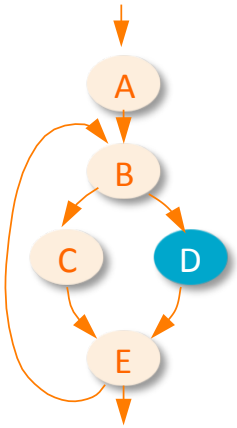


$\mathcal{C}^T$ = *all the theoreticaly-possible scenarios*

$\mathcal{C}^+$ = $\mathcal{C}^T$ – *known-to-be-infeasible scenarios*

$\mathcal{C}^r$ = *really-feasible scenarios*

$\mathcal{C}^-$ = *known-to-be-feasible scenarios*
or scenarios that cannot produce an execution time that is longer than $WCET^r$

Quantifying the pessimism of WCET estimates

Real WCET $\quad ET : \mathcal{H} \times \mathcal{P} \rightarrow \mathbb{N} \qquad WCET = \max_{(h,p)\in\mathcal{H}\times\mathcal{P}} ET(h,p)$

Static WCET estimation $\quad WCET^{\#} : \mathcal{H} \times \mathcal{P} \times \mathcal{C} \rightarrow \mathbb{N}$

- upper bound on the WCET:

$$WCET^{+} = \max_{(h,p,c)\in\mathcal{H}^{+}\times\mathcal{P}^{+}\times\mathcal{C}^{+}} ET(h,p,c)$$

$$WCET^{r} \leq WCET^{+}$$

- **lower bound** on the WCET:

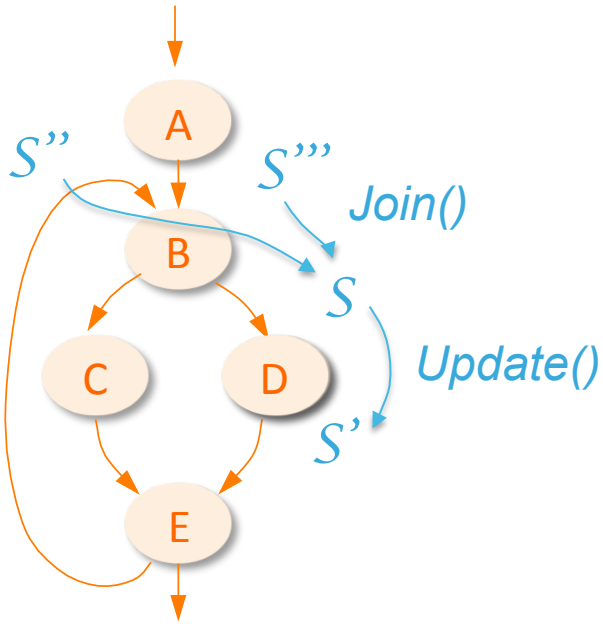
$$WCET^{-} \leq WCET^{r} \leq WCET^{+}$$

$U = WCET^{+} - WCET^{-}$

$$WCET^{-} = \max_{(h,p,c)\in\mathcal{H}^{-}\times\mathcal{P}^{-}\times\mathcal{C}^{-}} ET(h,p,c)$$

Example: pessimism of cache analysis

Background on static cache analysis



- *abstract interpretation*
- *cache state = ages of cache blocks* (0..A)
- *May and Must analyses*
- *categories assigned to cache accesses*
  - *AlwaysHit*
  - *AlwaysMiss*
  - *Persistent*
  - *NotClassified*

Example: pessimism of cache analysis

Low-level analysis scenarios

- C^{T} = {mmm, mmh,mhm, mhh, hmm, hmh, hhm, hhh}
- C^{+} = {hmm, hmh, hhm, hhh}
- C^{r} = {hmh, hhm, hhh}
- C^{-} = {hhh}

basic block

AlwaysHit

NotClassified

NotClassified

Example: pessimism of cache analysis

Experimental methodology

- hardware platform (model):
  - MPC5554-like pipeline
  - 4 KB, 4-way associative LRU instruction & data caches
    - infinite write buffer
- benchmarks from the TACLeBench collection (MediaBench)

benchmark	# accesses to I$	# loads
cjpeg_jpeg6b_wrbmp	37,328	6,187
gsm	4,2319,41	895,605
gsm_decode	1,739,854	211,854
gsm_encode	2,378,890	681,917
h264dec_ldecode_block	11,942	1,802
h264dec_ldecode_macroblock	51,373	51,373

Example: pessimism of cache analysis

Experimental methodology

- hardware platform (model):
  - MPC5554-like pipeline
  - 4 KB, 4-way associative LRU instruction & data caches
    - infinite write buffer
- benchmarks from the TACLeBench collection (MediaBench)
- WCET analysis with the OTAWA toolset ($WCET^{+}$)
  - we added the computation of $WCET^{-}$

Example: pessimism of cache analysis

Global results (instruction + data caches)

benchmark	$U = (\mathbf{WCET}^{+} - \mathbf{WCET}^{-})/\mathbf{WCET}^{-}$
cjpeg_jpeg6b_wrbmp	36.25%
gsm	161.95%
gsm_decode	96.33%
gsm_encode	216.00%
h264dec_ldecode_block	126.11%
h264dec_ldecode_macroblock	144.41%

Example: pessimism of cache analysis

Uncertainty of instruction cache analysis

- with pessimistic data cache analysis

benchmark	*PERS*	*NC*	$U_{i\$}$
cjpeg_jpeg6b_wrbmp	25.0%	5.1%	0.54%
gsm	34.9%	19.6%	2.36%
gsm_decode	38.4%	29.3%	1.83%
gsm_encode	31.5%	18.7%	2.29%
h264dec_ldecode_block	52.6%	18.8%	4.84%
h264dec_ldecode_macroblock	57.7%	1.8%	0.32%

Example: pessimism of cache analysis

Uncertainty of data cache analysis

- with pessimistic instruction cache analysis

benchmark	*PERS*	*NC*	*unknown @*	U_{ds}
cjpeg_jpeg6b_wrbmp	9.2%	46.1%	33.8%	35.29%
gsm	0.0%	55.8%	38.4%	66.25%
gsm_decode	0.0%	69.4%	52.6%	143.66%
gsm_encode	0.0%	51.7%	34.1%	190.01%
h264dec_ldecode_block	0.0%	80.5%	64.4%	82.51%
h264dec_ldecode_macroblock	0.0%	54.4%	22.1%	141.90%

Summary

Framework

- static analysis provides a guaranteed WCET upper bound ($WCET^{+}$)
- we can compute a lower bound on the WCET ($WCET^{-}$)
- the real WCET must be between $WCET^{-}$ and $WCET^{+}$
  - uncertainty $U = WCET^{+} - WCET^{-}$

Possible interpretations of U

- is my WCET estimation tight?
  - if not, it might be due to a poor analysis or to a poorly coded application
- how do two analyses of the same component compare?
- which parts of the application would deserve a more precise analysis?

TIME FOR QUESTIONS
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