From Trusted Annotations to Verified Knowledge

or

Squeeze your Trusted Annotation Base!

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Fact: Compile-Time Analysis is Limited

- Compiler Optimization
  - Less severely hit
    - strikes power/optimality, not usefulness
    - **but** opens the avenue to take advantage of the trade-off between precision and performance
- Worst-case Execution Time Analysis (WCET)
  - Severely hit
    - strikes **tightness**, not just power/optimality:

      No loop bound, no WCET bound!
    - unclear, how to take advantage of the trade-off between precision and performance

    $\leadsto$ **hence:** rest on **user-assistance!**

Motivation

Resting on user-assistance, however, means introducing a...

Trusted Annotation Base (TAB)

into WCET Analysis

Unintended but unavoidable consequences...

- Soundness: Computed time bounds hold only up to the correctness of the TAB - are we still safe ?
- Optimality: Same for tightness

Replacing Trust by Proof

- From Trust to Proof
  - Squeeze the TAB: Compress it!
    - Soundness: – Replacing trust by proof
      – Getting rid of user-assistance
    - Optimality: Sharpening the time bounds
- From Proof to Power
  - Squeeze the TAB/VAB: Wring it!
    - Taking advantage of the TAB/VAB
    - Taking advantage of the trade-off between power and performance of analysis algorithms

Replacing Trust by Proof – Model-checking

- If something can't be bounded automatically, ask for user-assistance
- Apply model-checking to prove/disprove the user-provided bound

... controlled and guided by

- Binary Tightening

  sharpen the current bound

- Binary Widening

  find start value if the user annotation is missing or faulty

The TuBound Tool

So far, TuBound featured

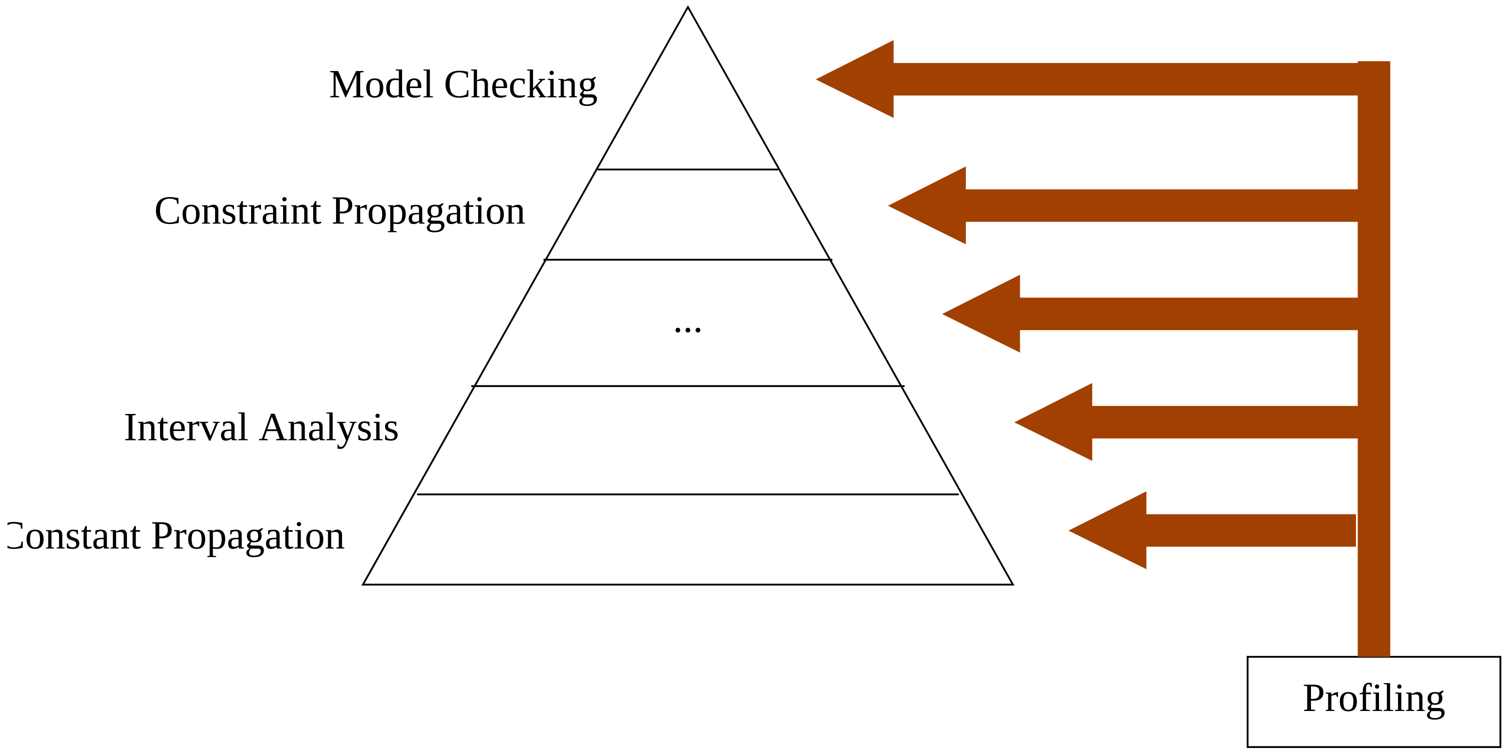
- Interval analysis
- Loop bound analysis
- Constraint analysis

to reduce the need for user-provided annotations to a minimum.

Recently, TuBound has been extended to feature

- Model-checking
  - BLAST
  - CBMC (turned out to be superior for our setting!)

Taking Advantage of TAB/VAB and Trade-Off...



...using a pool of complementary analysis techniques of different power and computational complexity.

Experimental Results (1)

Benchmark	Loops	TuBound basic	with Model Checking	Runtime
recursion	0	–	–	–
bsort100	3	100%	100%	–
cnt	4	100%	100%	–
cover	3	100%	100%	–
crc	3	100%	100%	–
edn	12	100%	100%	–
expint	3	100%	100%	–
fdct	2	100%	100%	–
fibcall	1	100%	100%	–
jfdctint	3	100%	100%	–
lcdnum	1	100%	100%	–
ludcmp	11	100%	100%	–
matmult	5	100%	100%	–
ndes	12	100%	100%	–
ns	4	100%	100%	–
qurt	1	100%	100%	–
sqrt	1	100%	100%	–
st	5	100%	100%	–

Experimental Results (2)

Benchmark	Loops	TuBound basic	with Model Checking	Runtime
qsort-exam	6	0%	66.6%	$0.02s$
bs	1	0%	100%	$0.03s\%$
nsichneu	1	0%	100%	$5.59s$
statemate	1	0%	100%	$0.06s$
janne_complex	2	0%	100%	$0.18s$
minver	17	94.1%	100%	$0.06s$
fft1	11	54.5%	81.8%	$0.43s$
duff	2	50%	50%	$0s$
whet	11	90.9%	90.9%	$-$
adpcm	18	83.3%	83.3%	timeout
compress	8	25.0%	25.0%	timeout
fir	2	50%	50%	timeout
lms	10	60%	60%	timeout
insertsort	2	0%	0%	timeout
select	4	0%	0%	timeout
Total Percentage		77.0%	84.7%	

Conclusions

Configuration	Soundness	WCET Anal. Succeeds	Characterization
Class. Automatic PAs w/out user-assistance	Sound	May Fail	Insufficient
Class. Automatic PAs w/ user-annotations	Sound rel. to TAB	Always	State-of-the-Art
Class. Automatic PAs w/ user-ann. checking	Sound rel. to red. TAB	Always	Contribution
Soph. Automatic PAs w/out user-assistance	Sound	Always	**The Holy Grail**

Thank you!

Questions?

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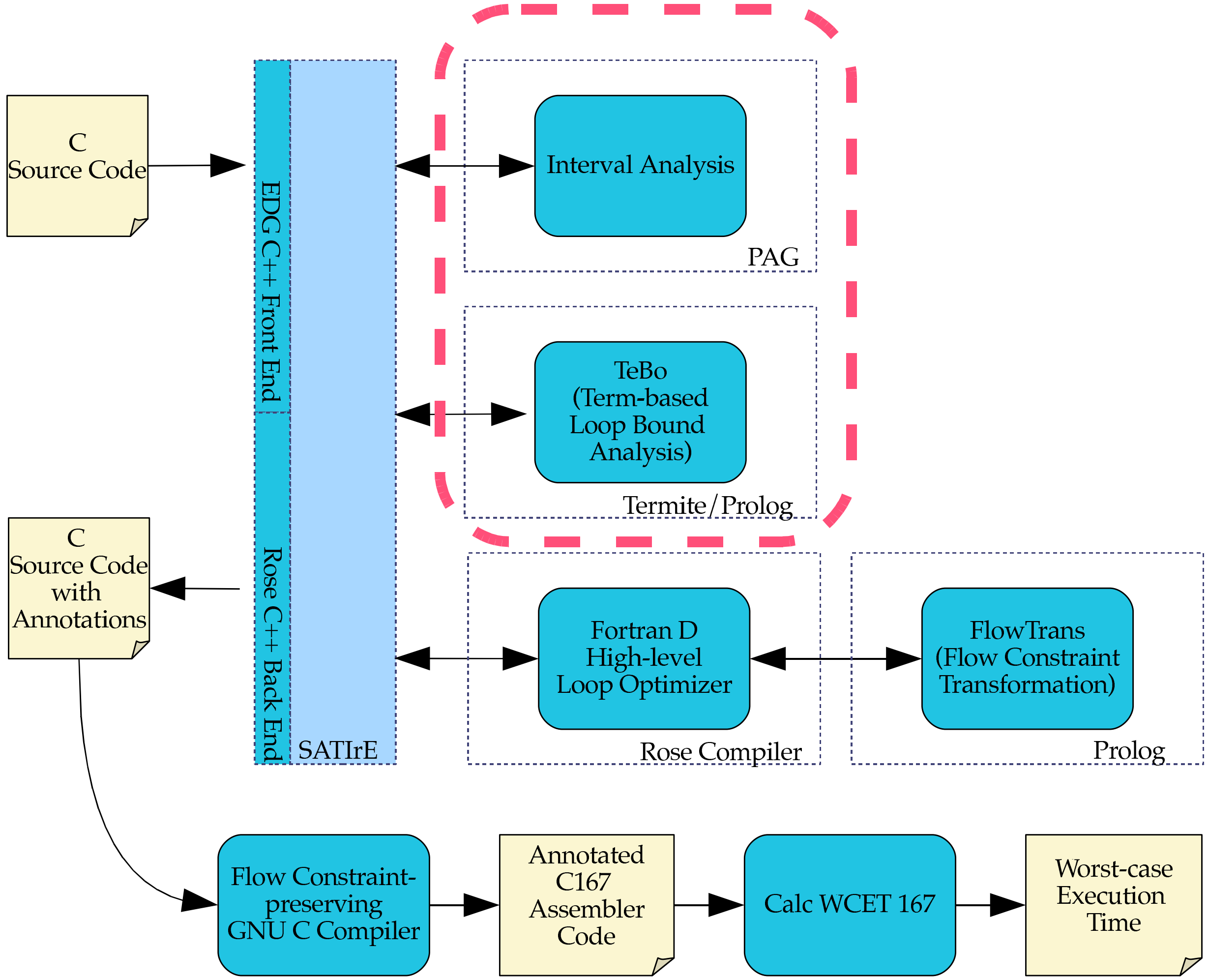
Experience: The TuBound Tool

Architecture overview...



Verifying Loop Bounds using CBMC

```
int binary_search(int x) {
  int fvalue, mid, low = 0, up = 14;
  fvalue = (-1); /* all data are positive */
  {
=>  unsigned int __bound = 0;
    while(low <= up){
      mid = low + up >> 1;
      if (data[mid].key == x) { /* found  */
        up = low - 1;
        fvalue = data[mid].value;
      }
      else if (data[mid].key > x)
        up = mid - 1;
      else low = mid + 1;

=>    __bound += 1;
    }
=>   assert(__bound <= 7);
  }
  return fvalue;
}
```

CBMC at Work: Replacing Trust by Proof

```
int complex(int a, int b)                    int complex(int a, int b)
{                                            {
  while(a < 30) {                              while(a < 30) {
#pragma wcet_trusted_loopbound(16)   <==>    #pragma wcet_loopbound(16)
      while(b < a) {                               {
#pragma wcet_trusted_loopbound(16)   <==             unsigned int __bound = 0U;
        if (b > 5)                                   while(b < a){
          b = b * 3;                 ==>     #pragma wcet_trusted_loopbound(16)
        else                                           ++__bound;
          b = b + 2;
        if (b >= 10 && b <= 12)    ------->            if (b > 5)
          a = a + 10;                                    b = b * 3;
        else                                           else
          a = a + 1;                                     b = b + 2;
      }                                                if (b >= 10 && b <= 12)
      a = a + 2;                                         a = a + 10;
      b = b - 10;                                      else
    }                                                    a = a + 1;
  return 1;                                         }
}                                                   a = a + 2;
...                                                 b = b - 10;
                                                  }
                                                  return 1;
                                                }
                                                ...
```