Software Security and Proved Compilation

Alexandre Pilkiewicz

Gallium Team

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- Broad area: Programming languages

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- Specifically:
  - Design of (functional) languages
  - Compilation
  - Type system
  - Programming safety

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Software Kind

Sensitive	Network Security	Data Security		
Ordinary	PC/Phone Software			

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Critical	Railways	Medical	Nuclear plants	Airplane
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A380: 800k loc

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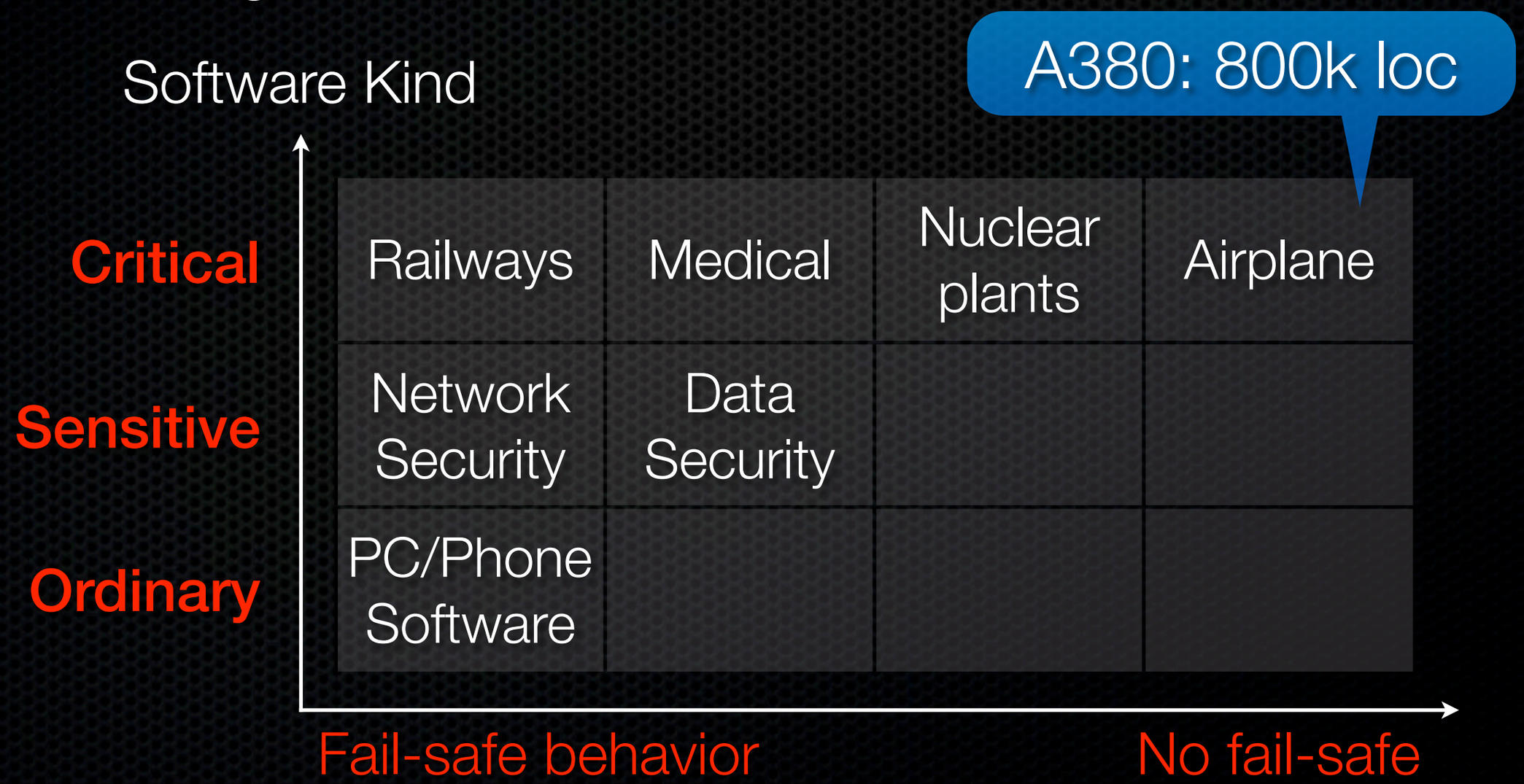

Medical: Therac 25 radiation therapy machine (1985-87)

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  - Megavolt X-ray (high dose on a metallic target)

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DO-178

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Ariane 5 launch
4 June 1996
$130 million direct cost

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  - New operator -> slow -> no bug
  - Better operator -> fast -> dead patient

More systematic tools

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Simulink,
Scade

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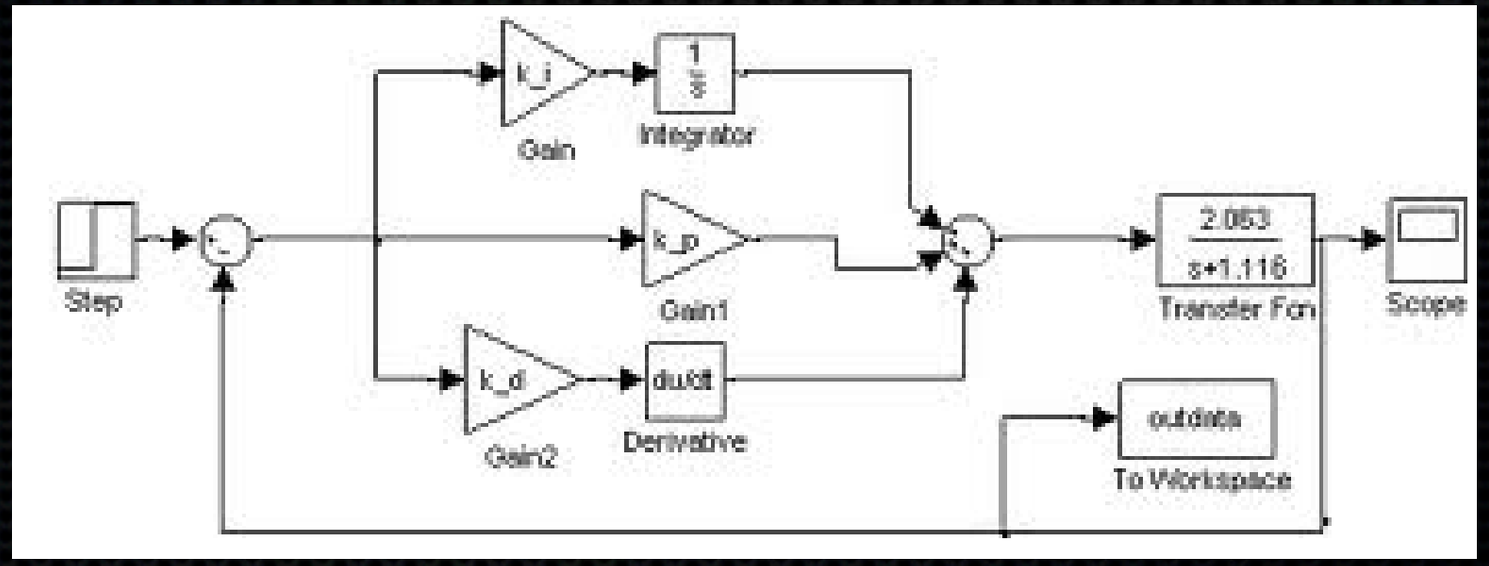

More systematic tools

Model checking/
Proofs → Simulink,
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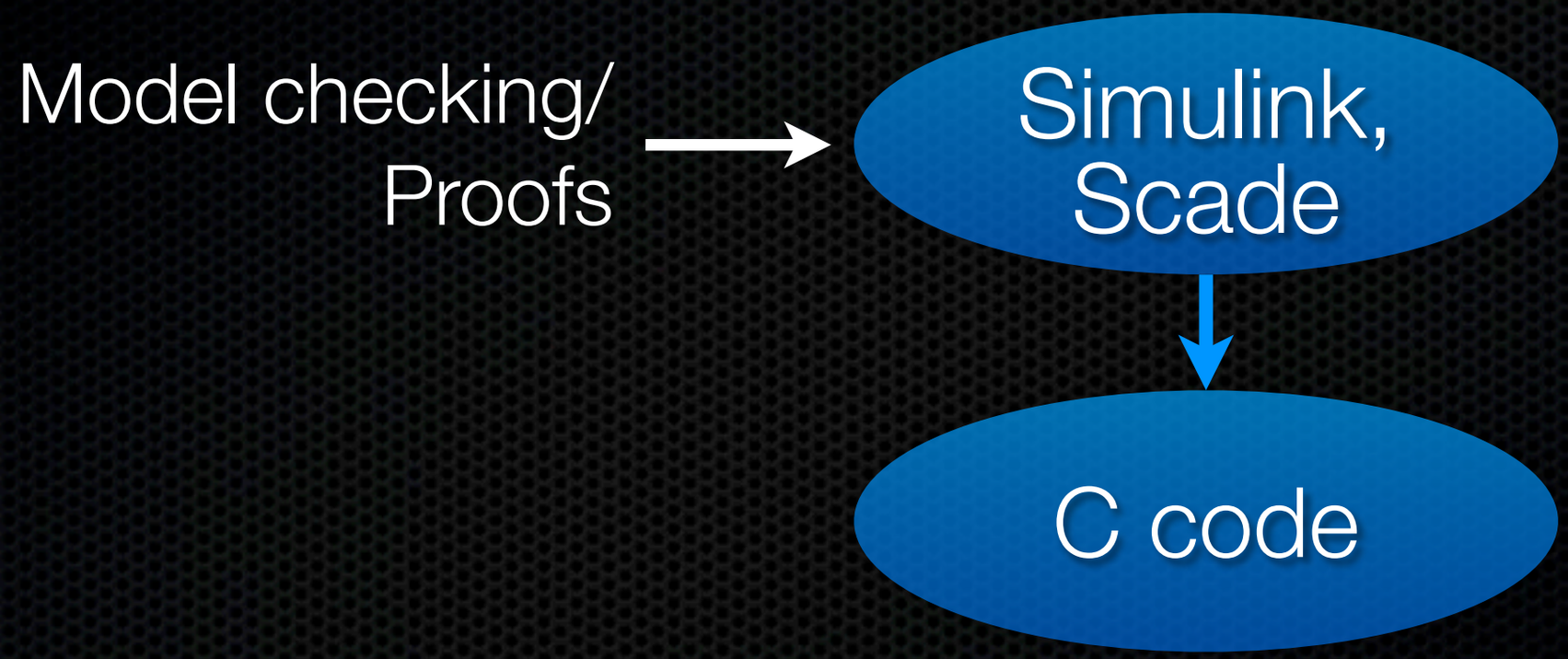

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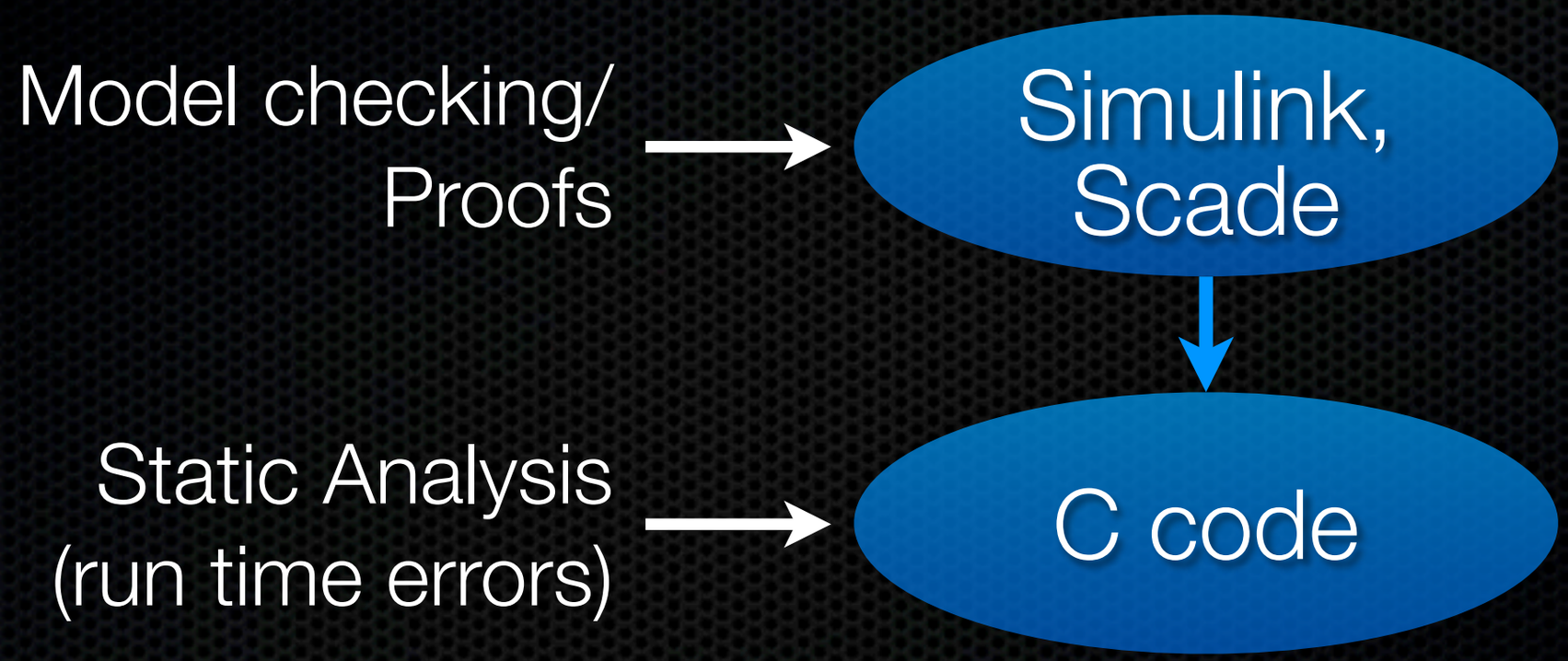

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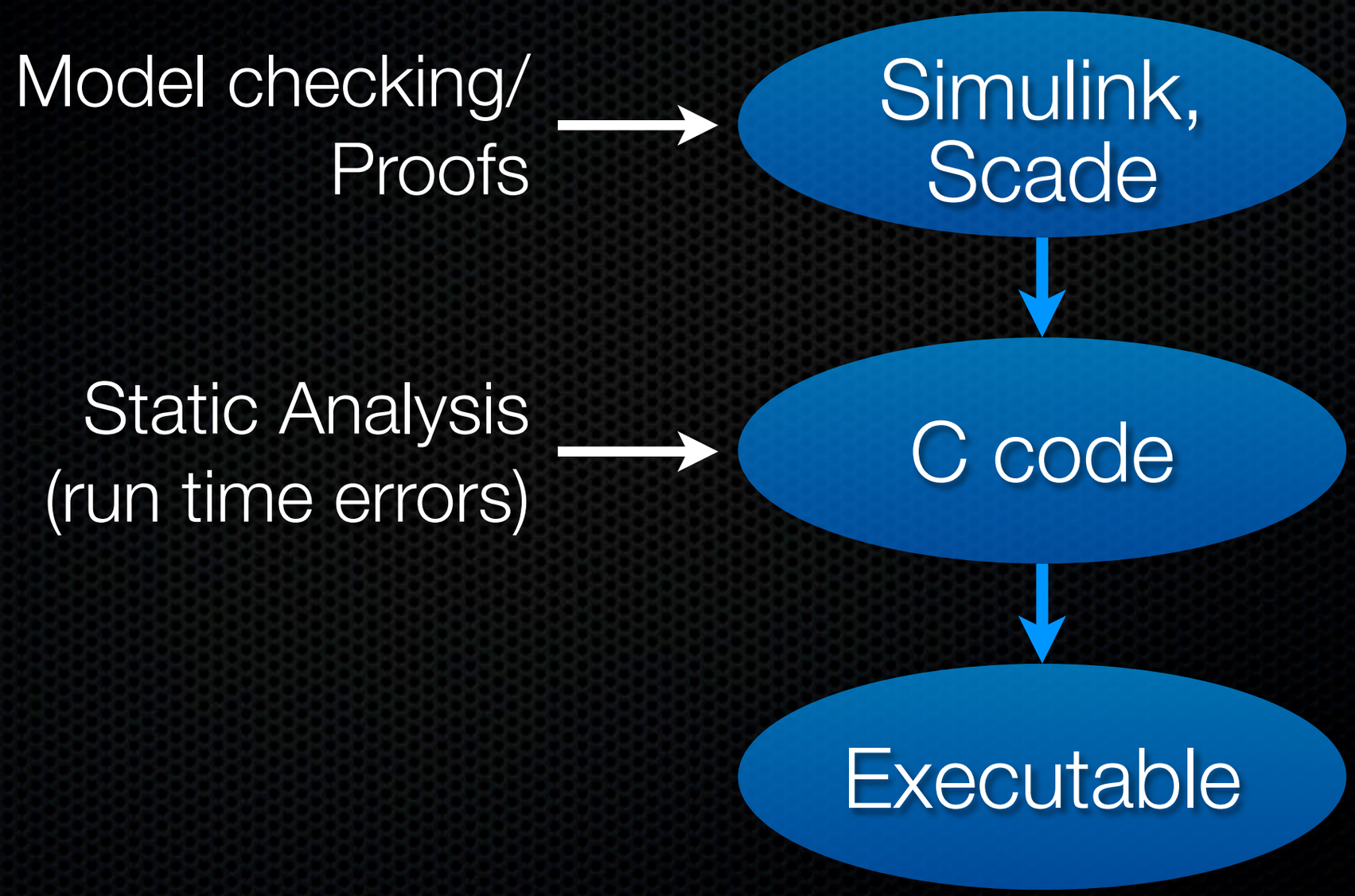

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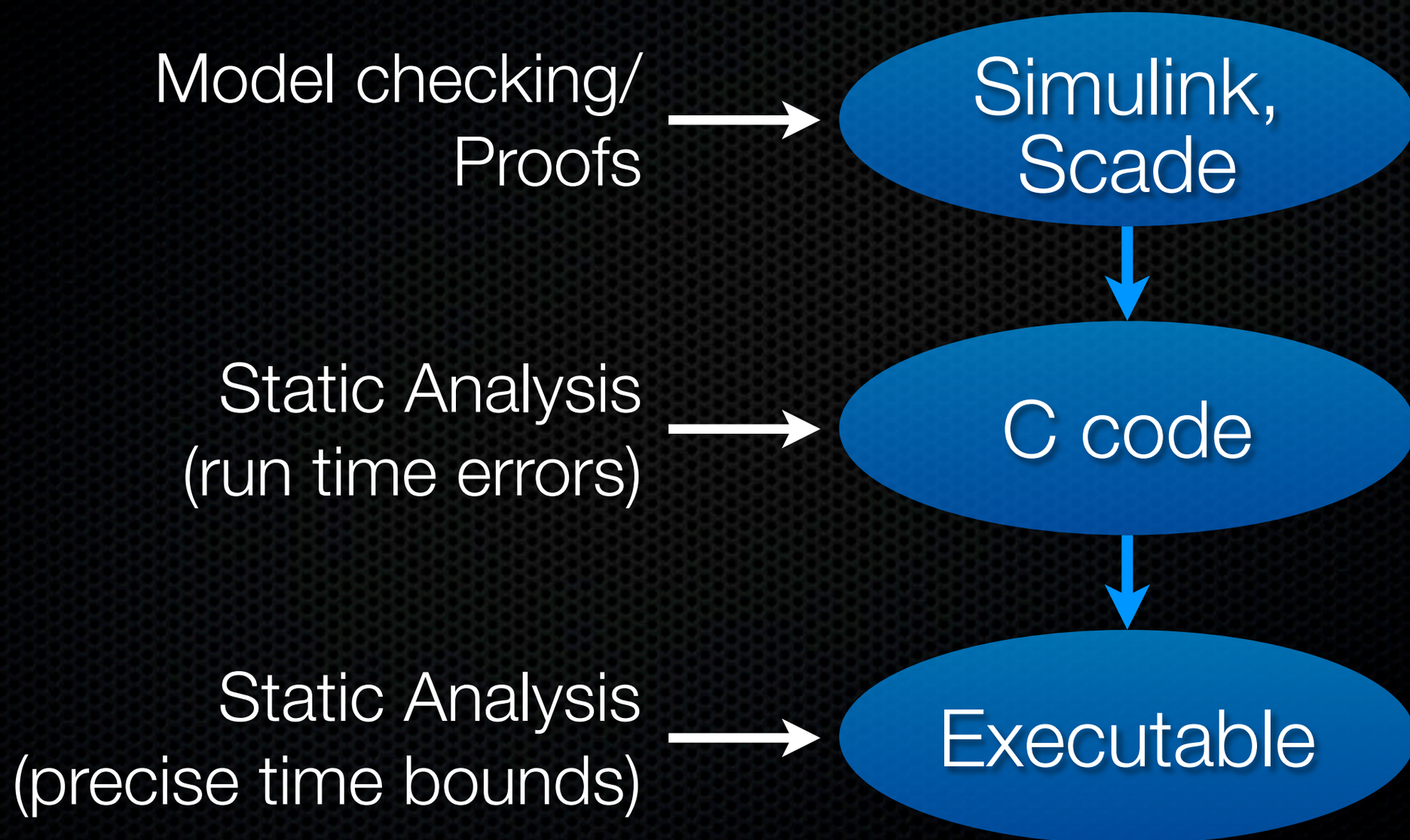

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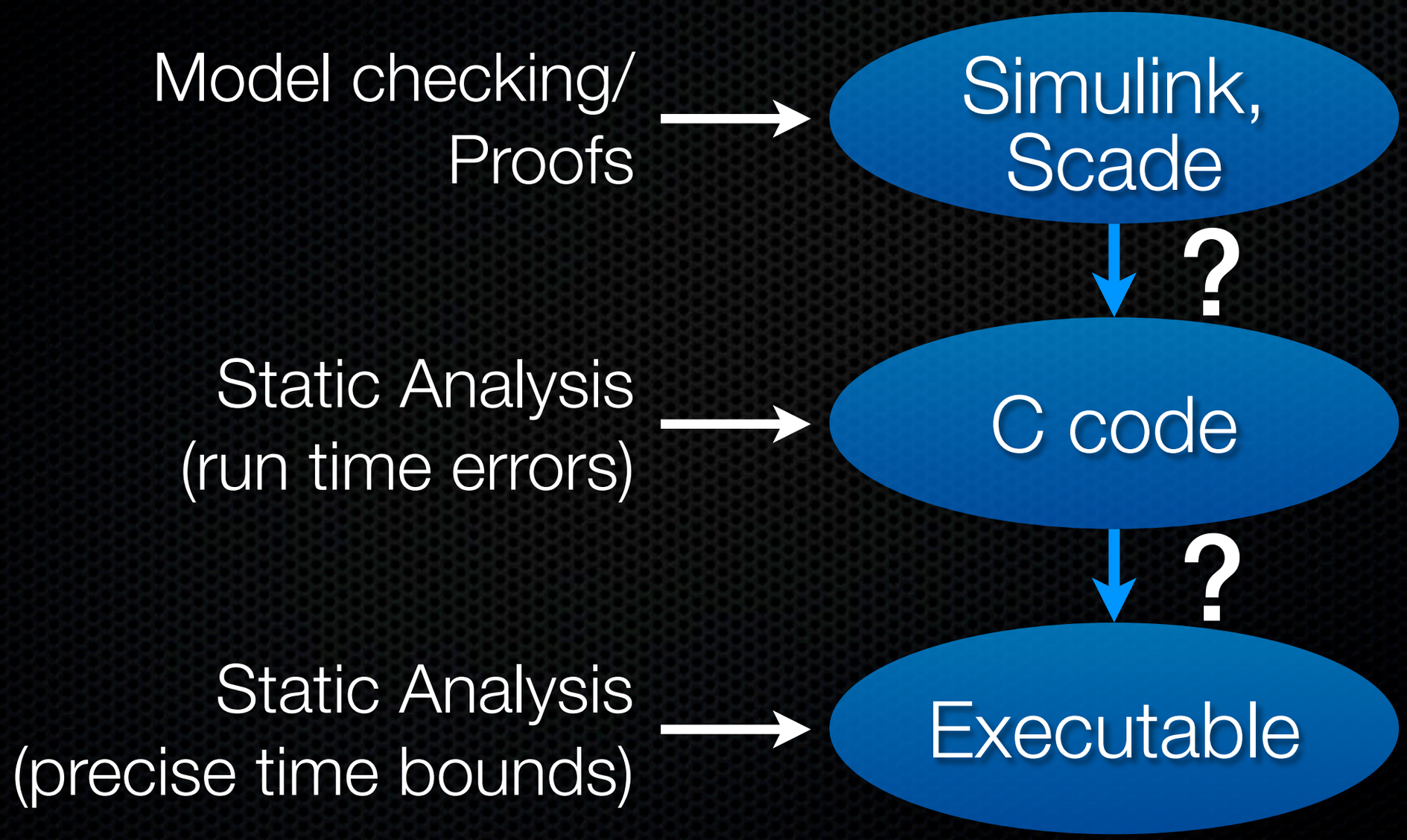

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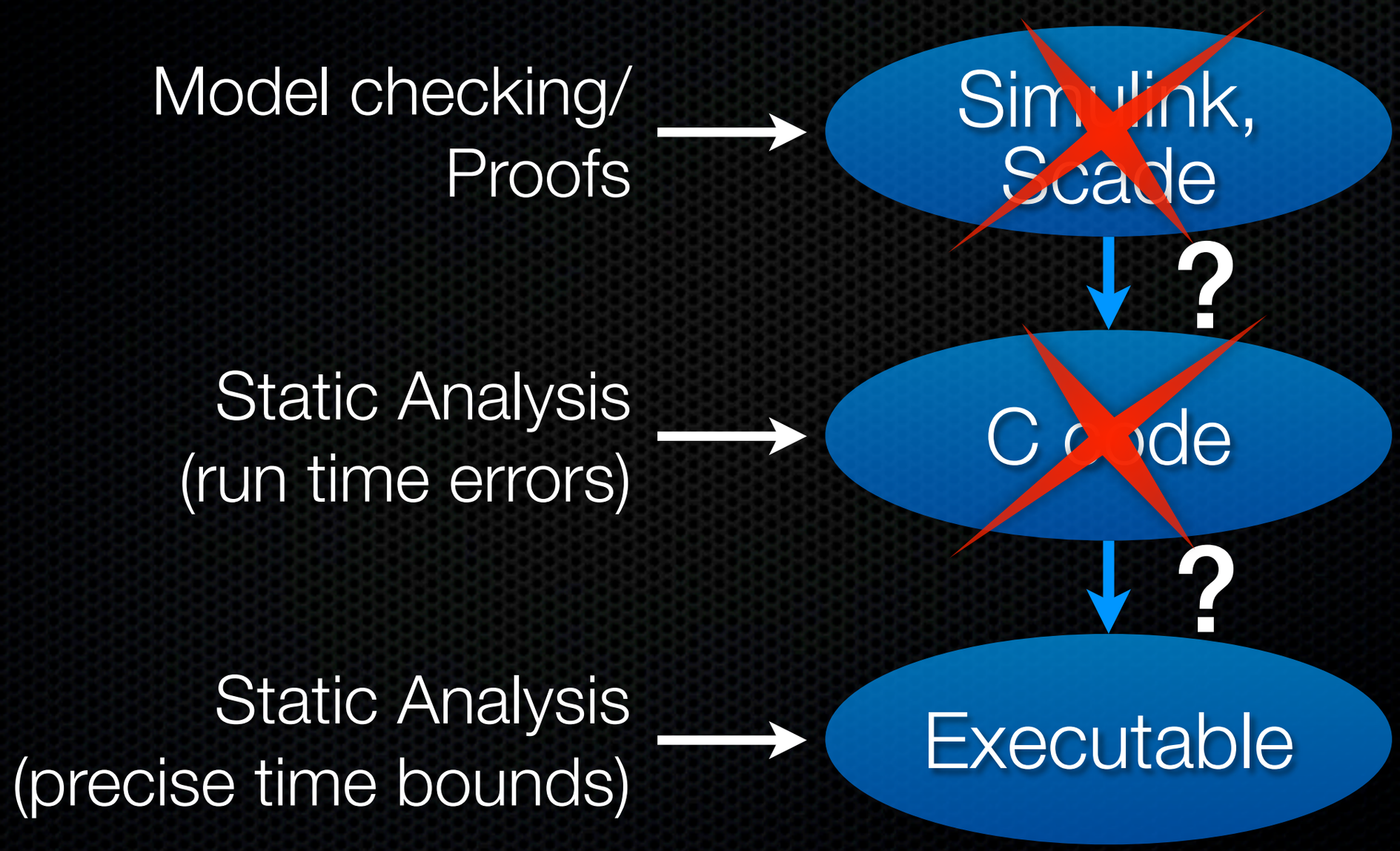

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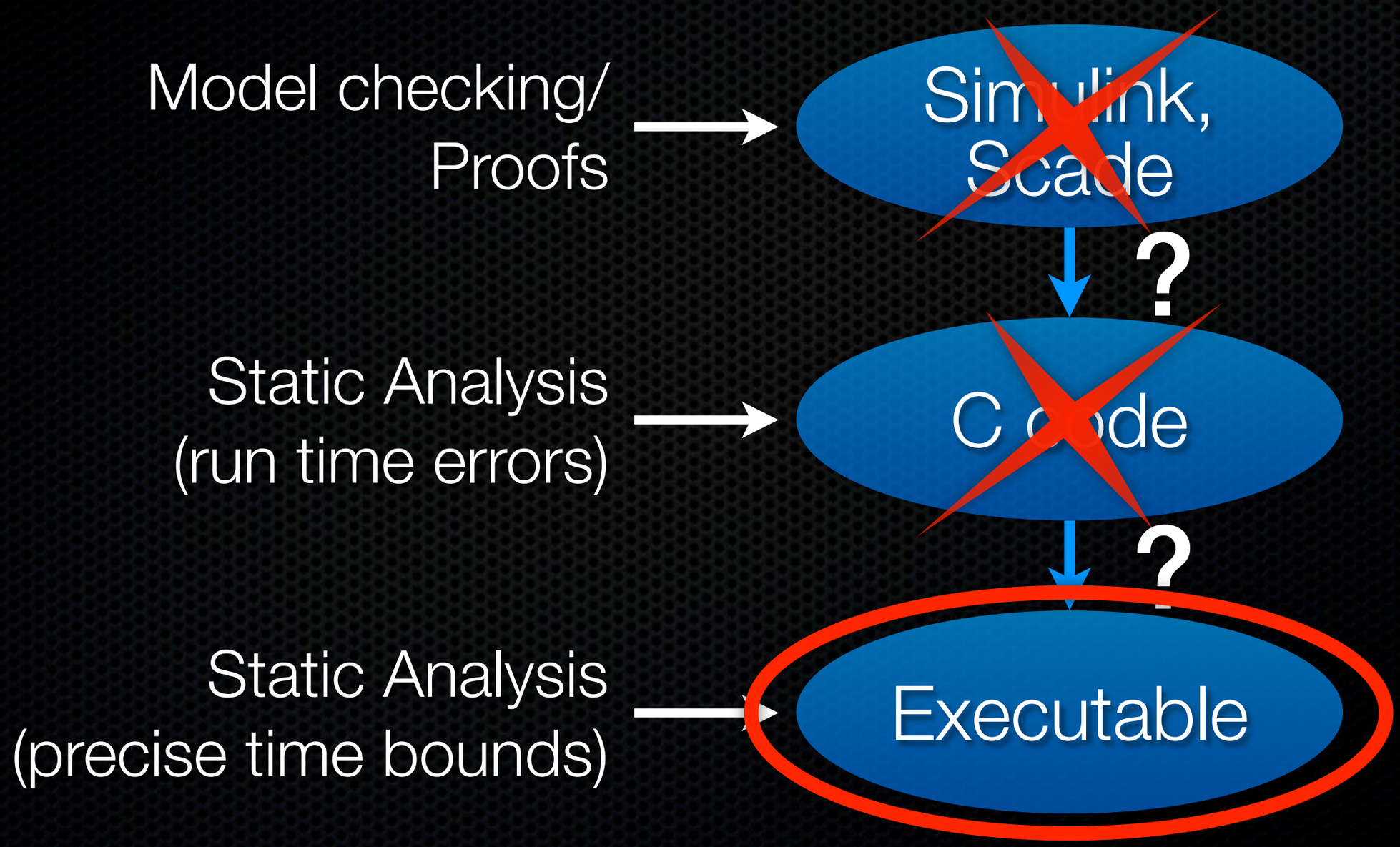

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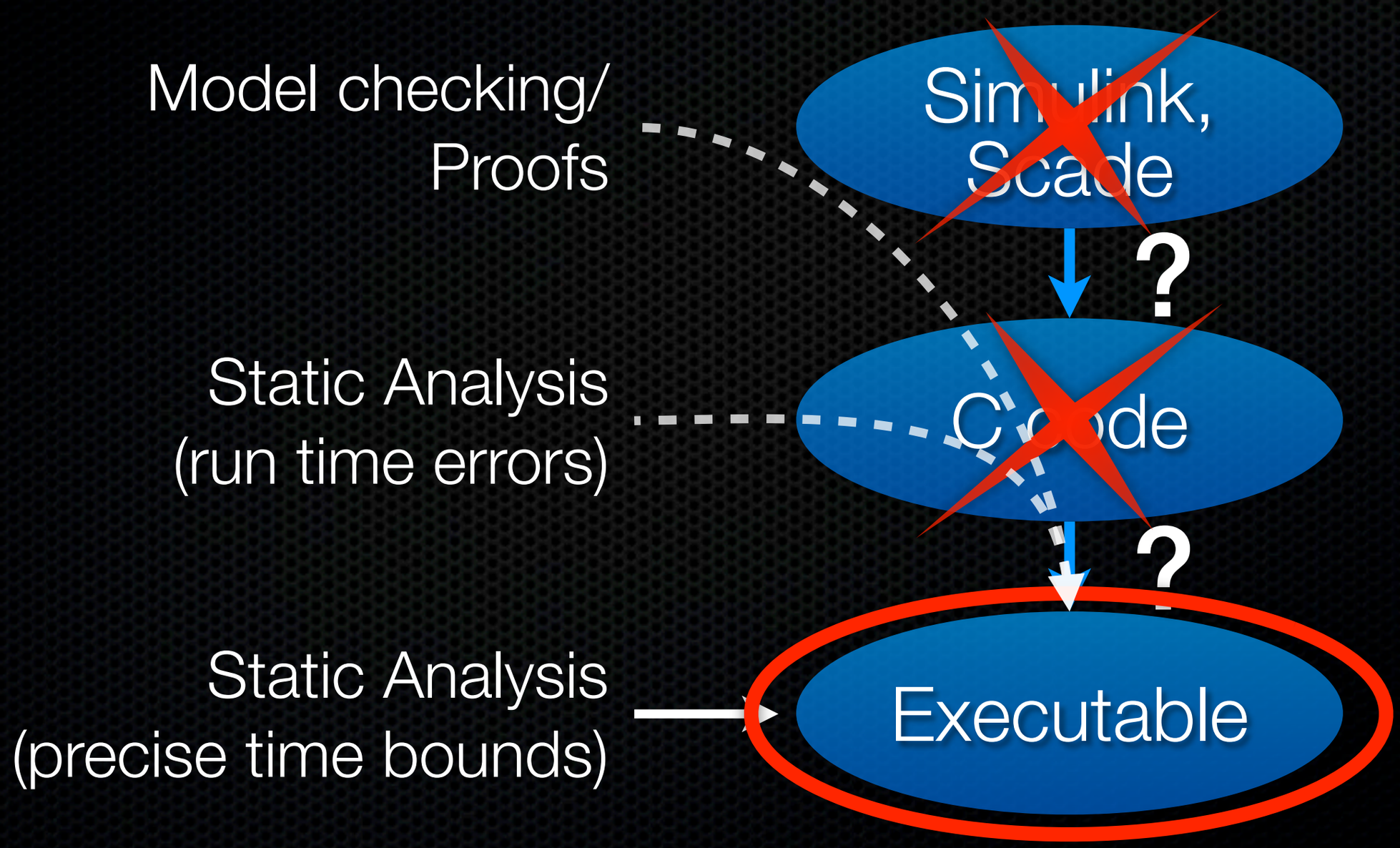

How complicated is a compiler?

```
double dotproduct(int n, double * a, double * b) {
  double dp = 0.0;
  int i;
  for (i = 0; i < n; i++)
    dp += a[i] * b[i];
  return dp;
}
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Compiled with Tru64/Unix and manually translated back to C...

...by Xavier Leroy

```
double dotproduct(int n, double a[], double b[]) {
  dp = 0.0;
  if (n ≤ 0) goto L5;
  r2 = n − 3; f1 = 0.0; r1 = 0; f10 = 0.0; f11 = 0.0;
  if (r2 > n || r2 ≤ 0) goto L19;
  prefetch(a[16]); prefetch(b[16]);
  if (4 ≥ r2) goto L14;
  prefetch(a[20]); prefetch(b[20]);
  f12 = a[0]; f13 = b[0]; f14 = a[1]; f15 = b[1];
  r1 = 8; if (8 ≥ r2) goto L16;
L17: f16 = b[2]; f18 = a[2]; f17 = f12 * f13;
  f19 = b[3]; f20 = a[3]; f15 = f14 * f15;
  f12 = a[4]; f16 = f18 * f16;
  f19 = f29 * f19; f13 = b[4]; a += 4; f14 = a[1];
  f11 += f17; r1 += 4; f10 += f15;
  f15 = b[5]; prefetch(a[20]); prefetch(b[24]);
  f1 += f16; dp += f19; b += 4;
  if (r1 < r2) goto L17;
L16: f15 = f14 * f15; f21 = b[2]; f23 = a[2]; f22 = f12 * f13;
  f24 = b[3]; f25 = a[3]; f21 = f23 * f21;
  f12 = a[4]; f13 = b[4]; f24 = f25 * f24; f10 = f10 + f15;
  a += 4; b += 4; f14 = a[8]; f15 = b[8];
  f11 += f22; f1 += f21; dp += f24;
L18: f26 = b[2]; f27 = a[2]; f14 = f14 * f15;
  f28 = b[3]; f29 = a[3]; f12 = f12 * f13; f26 = f27 * f26;
  a += 4; f28 = f29 * f28; b += 4;
  f10 += f14; f11 += f12; f1 += f26;
  dp += f28; dp += f1; dp += f10; dp+=f11;
  if (r1 ≥ n) goto L5;
L19: f30 = a[0]; f18 = b[0]; r1 += 1; a += 8; f18 = f30 * f18;
  b += 8; dp += f18;
  if (r1 < n) goto L19;
L5: return dp;
L14: f12 = a[0]; f13 = b[0]; f14 = a[1]; f15 = b[1]; goto L18;
```

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L17: f16 = b[2]; f18 = a[2]; f17 = f12 * f13;
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Yep

. . .

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  - 13 production-quality C compilers tested
  - 13 production-quality C compilers found buggy
  - Around 300 previously unknown bugs
- Just have a look at bug trackers...

But what exactly is a compiler bug?

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  - produces a function that returns 42

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Solutions?

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DO-178

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DO-178

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DO-178

Solutions?

- Testing?
- Very simple compiler, manually checked executable
- Proving it correct!
  - Clear and precise specification
  - Yes, feasible! CompCert (4 person.years, Leroy & al.)

DO-178

How to prove programs?

- Method B
- Program in C, prove with Frama-C
- Program in Coq, prove in Coq
- ...

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-u:-- *goals* All L1 (Co

-u:-- exemple.v Bot L6 (co -u:-- *response* All L1 (Co

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```
Definition square (x:Z): Z :=
  x * x.
```

-u:** exemple.v Bot L7 (co

-u:-- *goals* All L1 (Co

```
square is defined
```

-u:-- *response* All L1 (Co

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```
Definition square (x:Z): Z :=
  x * x.

Lemma square_positive:
  forall (x:Z), square x >= 0.
Proof.
```

-u:** exemple.v Bot L11 (co

```
1 subgoal

  ============================
   forall x : Z, square x >= 0
```

-u:-- *goals* All L4 (Co

-u:-- *response* All L1 (Co

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```
Definition square (x:Z): Z :=
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Lemma square_positive:
  forall (x:Z), square x >= 0.
Proof.
  unfold square.
```

-u:** exemple.v Bot L12 (co

```
1 subgoal

  ============================
   forall x : Z, x * x >= 0
```

-u:-- *goals* All L4 (Co

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```
Definition square (x:Z): Z :=
  x * x.

Lemma square_positive:
  forall (x:Z), square x >= 0.
Proof.
  unfold square.
  intro x.
  destruct x.
```

-u:-- exemple.v Bot L14 (co

```
3 subgoals

  ============================
   0 * 0 >= 0

subgoal 2 is:
 Zpos p * Zpos p >= 0
subgoal 3 is:
 Zneg p * Zneg p >= 0
```

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-u:-- *response* All L1 (Co

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Definition square (x:Z): Z :=
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Lemma square_positive:
  forall (x:Z), square x >= 0.
Proof.
  unfold square.
  intro x.
  destruct x.
  compute; congruence.
  compute; congruence.
```

-u:** exemple.v Bot L17 (co

-u:-- *goals* All L1 (Co

```
Proof completed.
```

-u:-- *response* All L1 (Co

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```
Definition square (x:Z): Z :=
  x * x.

Lemma square_positive:
  forall (x:Z), square x >= 0.
Proof.
  unfold square.
  intro x.
  destruct x.
  compute; congruence.
  compute; congruence.
Qed.
```

-u:** exemple.v Bot L18 (co

-u:-- *goals* All L1 (Co

```
square_positive is defined
```

-u:-- *response* All L1 (Co

Correct Compiler?

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`prog_c`

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compile prog_c = OK
```

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compile prog_c = OK executable
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Correct Compiler?

- Terminate or not
- Returned value
- Input/Output

```
  compile prog_c = OK executable
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```

Correct Compiler?

- Terminate or not
- Returned value
- Input/Output
- System calls
- Volatile memory access

```
  compile prog_c = OK executable
∧ Has_Behavior beh executable
```

Correct Compiler?

```
  compile prog_c = OK executable
∧ Has_Behavior beh executable
→ Has_Behavior beh prog_c.
```

Correct Compiler?

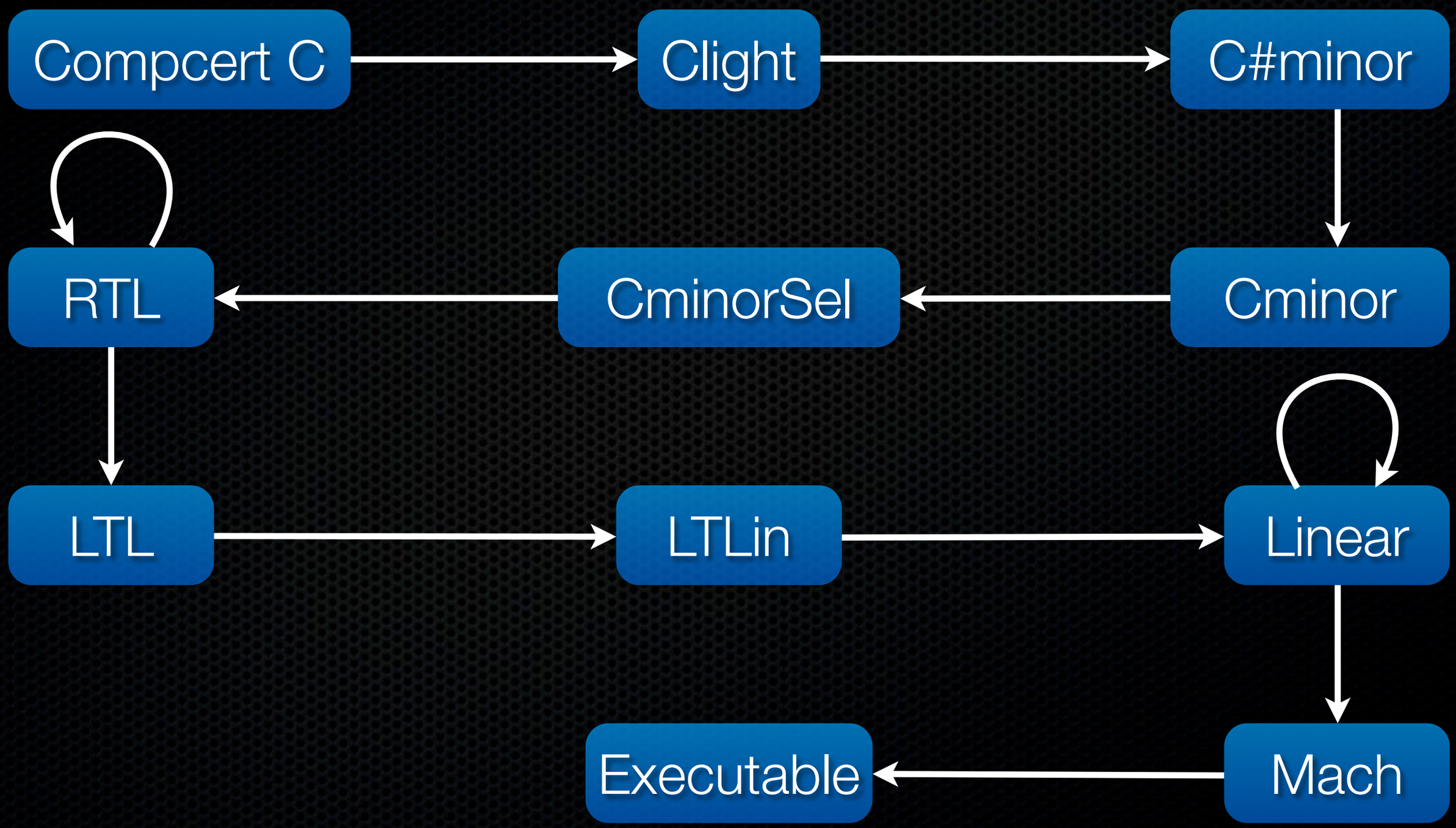
```
Theorem compiler_correct:
  ∀ prog_c executable beh,
    compile prog_c = OK executable
  ∧ Has_Behavior beh executable
  → Has_Behavior beh prog_c.
```

Everything proved at once?

Compcert C

Executable

Everything proved at once?



Proof of optimizations

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- Implement it in Coq and prove it

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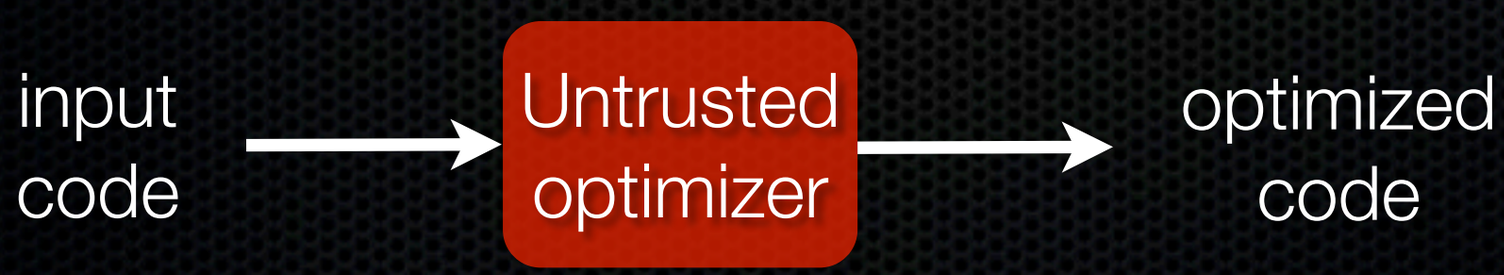
- «Off the shelf» optimizer, proved validator



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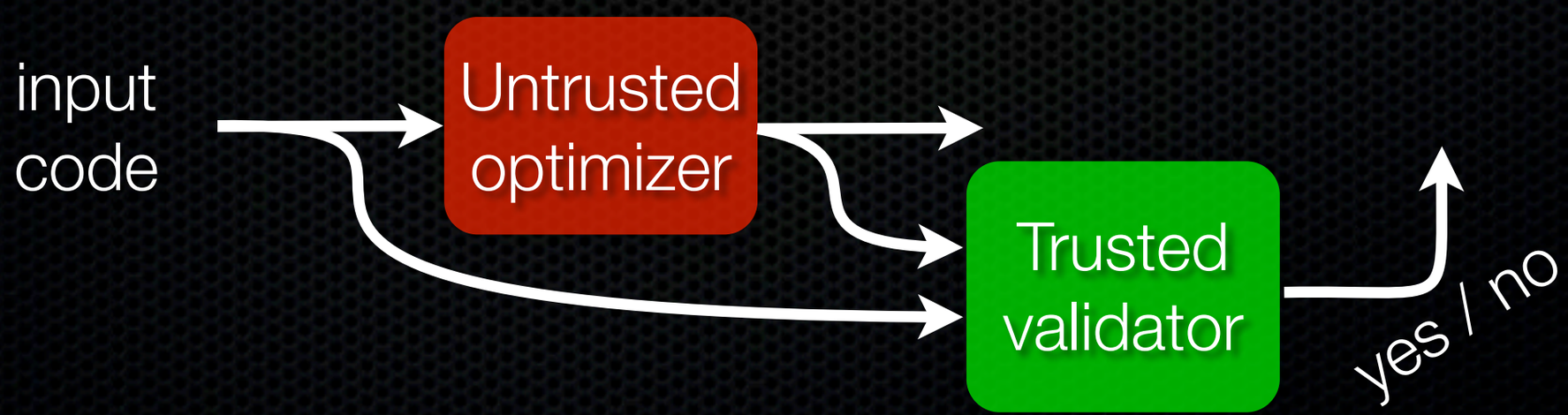

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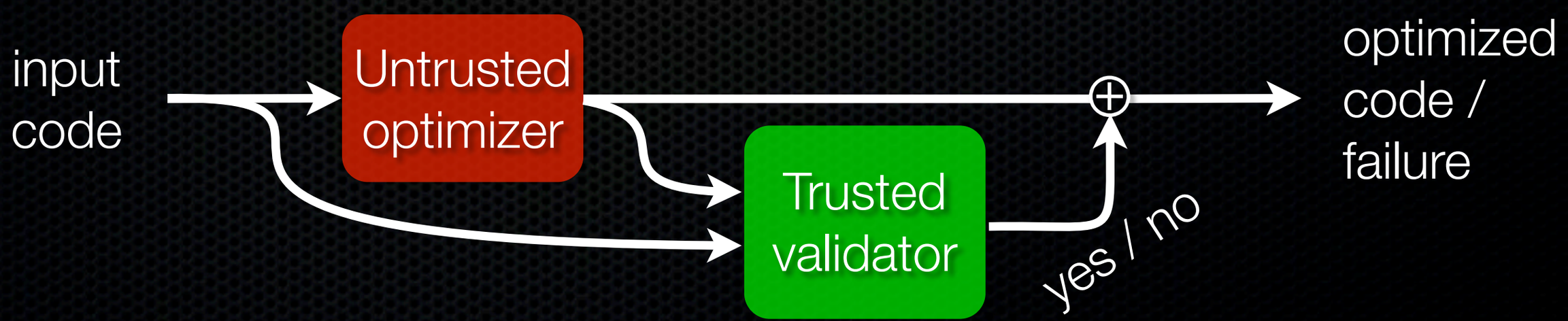

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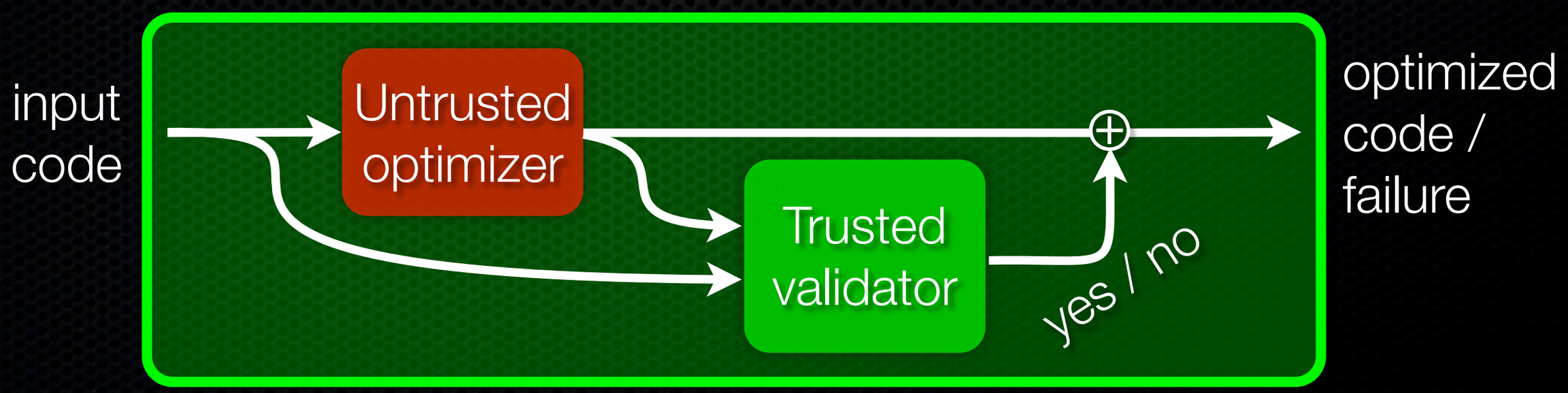

Validated optimizations

- Lazy code motion
- Software pipelining
- ...
- Polyhedral optimizations

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Optimizing loop nests

Polyhedral optimizations

```
for c = 0 to nb_c
  for l = 0 to nb_l
    M[l][c] = 0;
  done;
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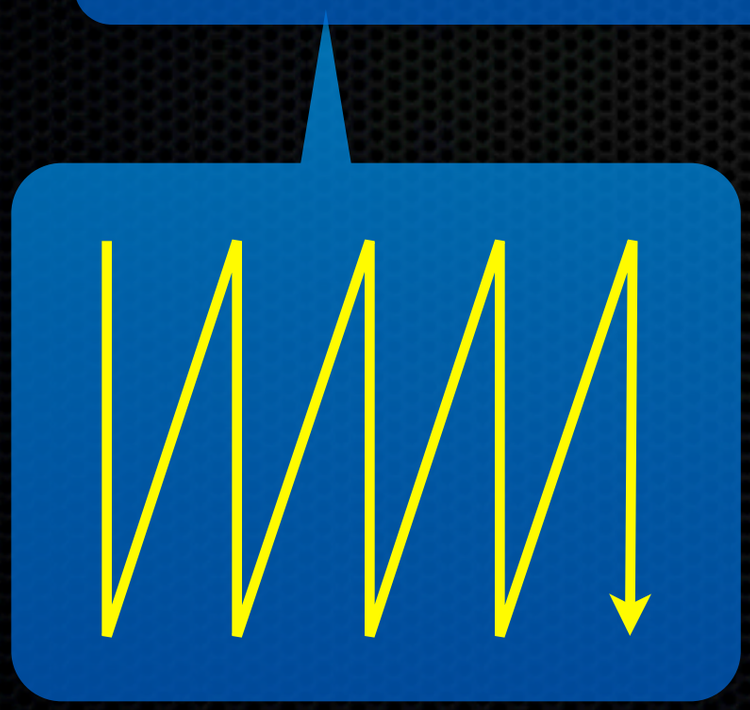

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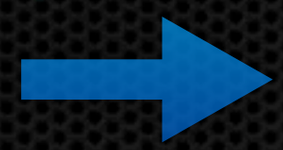

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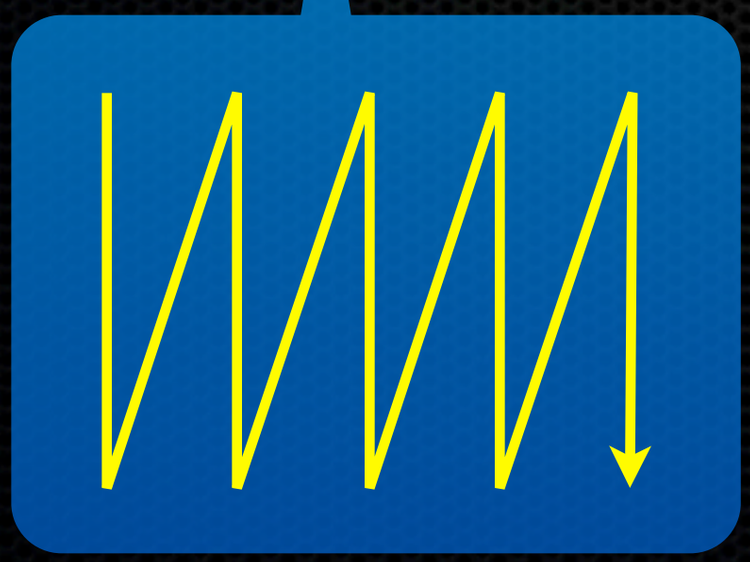

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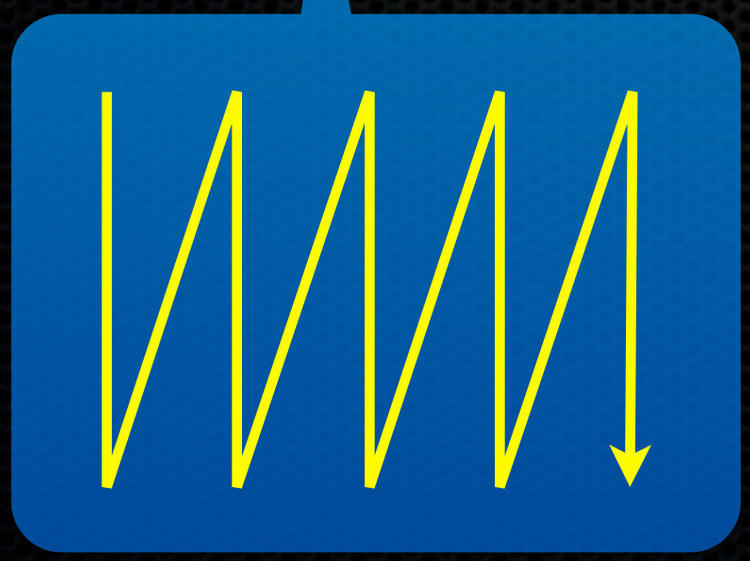

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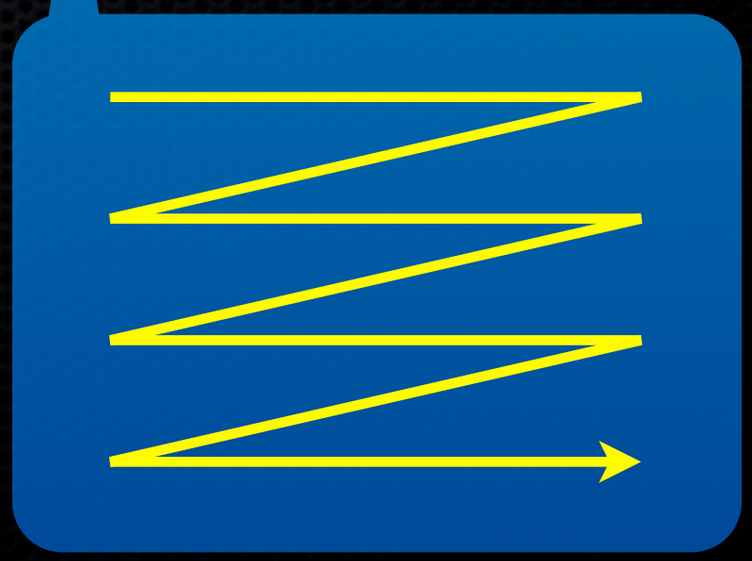
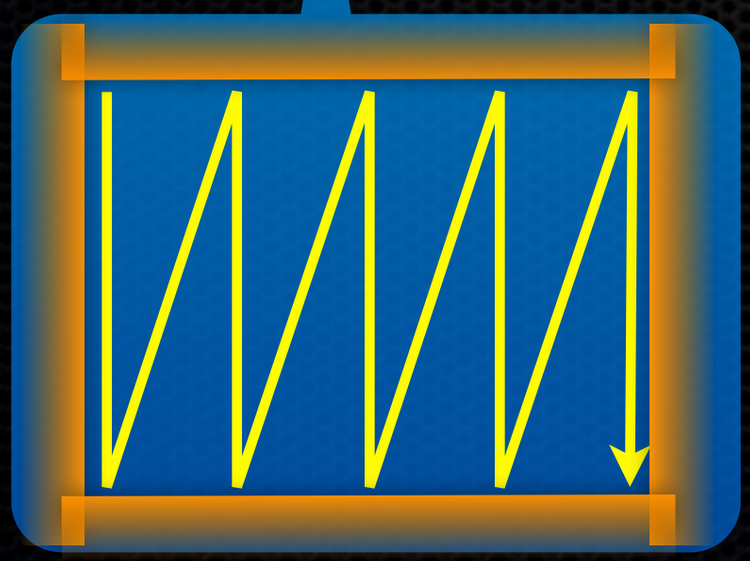
done;
```

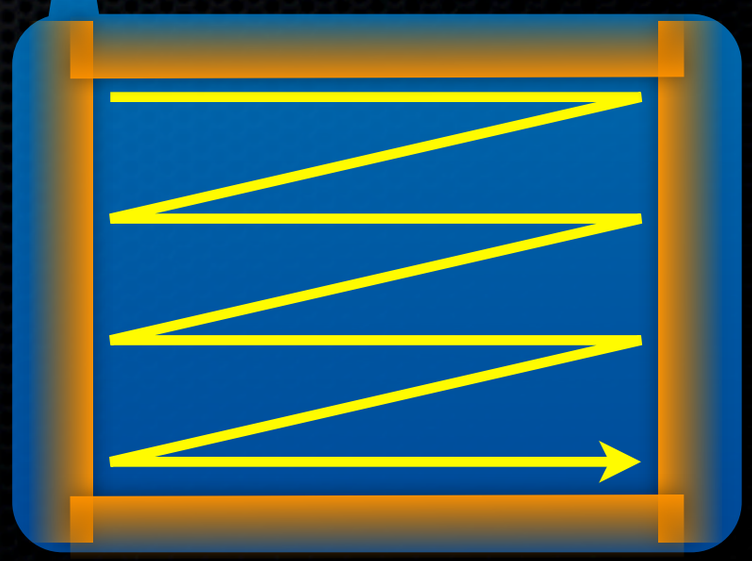


Polyhedral optimizations

```
for c = 0 to nb_c
  for l = 0 to nb_l
    M[l][c] = 0;
  done;
done;
```



```
for l = 0 to nb_l
  for c = 0 to nb_c
    M[l][c] = 0;
  done;
done;
```



Take home message

- Bugs are dangerous
- You can (and even should) prove your code
- You then need a proved compiler
- Such a compiler exists
- and is getting better!