Synthesis-Enabled Translation

CSE 501

Spring 15

Announcements

- Office hour today 3-4, CSE 530
- Project presentations on Thursday
  - 10 min presentation for each group
  - 2 min for questions
- Project final report and HW 2 due on June 9th

Outline for today

- Synthesis background
- Using synthesis to build compilers

- Two domain studies
  - Database applications
  - Stencils

What is synthesis

The promise

Automate the task of writing programs

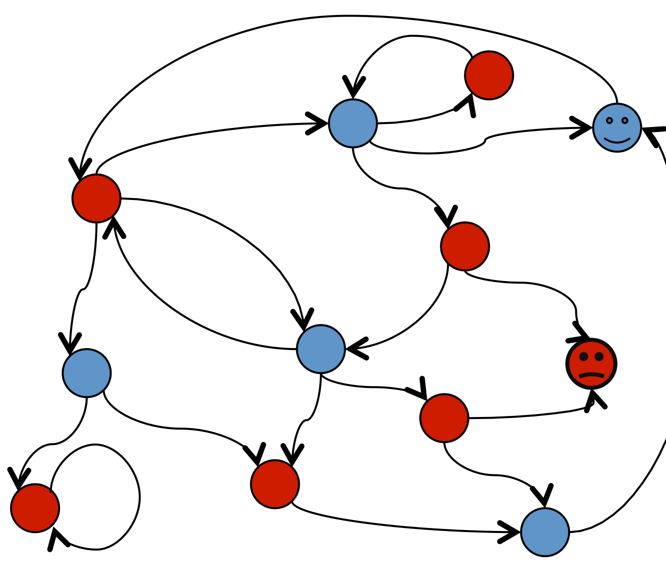
What do we mean by synthesis

- We want to get code from high-level specs
  - Python and VB are pretty high level, why is that not synthesis?

- Support compositional and incremental specs
  - Python and VB don't have this property
    - If I don't like the way the python compiler/runtime is implementing my program, I am out of luck.
  - Logical specifications do
    - I can always add additional properties that my system can satisfy
  - Specs are not only functional
    - Structural specifications play a big role in synthesis
    - How is my algorithm going to look like.

The fundamental challenge

- The fundamental challenge of synthesis is dealing with an uncooperative environment
  - For reactive systems, people model this as a game
    - For every move of the adversary (ever action of the environment), the synthesized program must make a counter-move that keeps the system working correctly.
    - The game can be modeled with an automata



The fundamental challenge

- The fundamental challenge of synthesis is dealing with an uncooperative environment
  - If we are synthesizing functions, the environment provides the inputs
  - i.e. whatever we synthesize must work correctly for all inputs
- This is modeled with a doubly quantified constraint
  - if the spec is given as pre and post conditions, then:
  - $\exists P. \forall \sigma. (\sigma \models \{pre\}) \Rightarrow (\sigma \models WP(P, \{post\}))$
- But what does it mean to quantify over the space of programs??

Quantifying over programs

- Synthesis in the functional setting can be seen as curve fitting
  - i.e. we want to find a curve that satisfies some properties

- It's very hard to do curve fitting when you have to consider arbitrary curves
  - Instead, people use *parameterized* families of curves
  - This means you quantify over parameters instead of over functions

- This is the first fundamental idea in software synthesis
  - People call these Sketches, scaffolds, templates, …
  - They are all the same thing

Formalizing the synthesis problem

- $\exists P. \forall \sigma. (\sigma \models \{pre\}) \Rightarrow (\sigma \models WP(P, \{post\})$
- $\exists P. \forall in. P(in) \models \phi$
  - ϕ represents the specification
- $\exists c. \forall in. Sk(c, in) \models \phi$
- $\exists c. \forall in. Q(c, in)$

- Many ways to represent Q
  - Can model as a boolean predicate at the abstract level

Dealing with quantifiers

- Eliminate symbolically
  - You can use an abstract domain
  - You can use plain-vanilla elimination (not recommended)
- Sample the space of inputs intelligently

Solving the synthesis problem

- Deductive synthesis
  - Write rules to describe all possible derivations from spec to actual program
  - Provably correct since only semantic-preserving programs are explored
  - Requires axiomatization of domain and complete spec from user
  - Example: Denali

Solving the synthesis problem

- Inductive synthesis
  - User gives examples of input / output of P
    - Essentially a *partial* specification
  - Requires no axioms
  - Search can take significant amount of time

Inductive synthesis: example

Define parameterized programs explicitly

– Think of the parameterized programs as "programs with holes"

Example: Hello World of Sketching

spec:

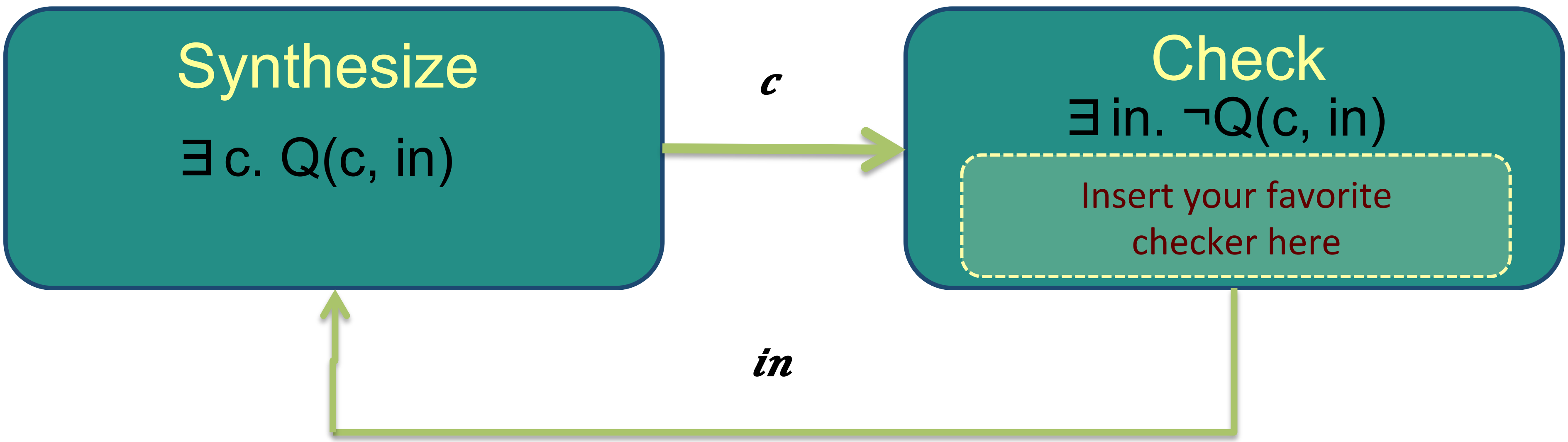
```
int foo (int x)
{
    return x + x;
}
```

sketch:

```
int bar (int x) implements foo
{
    return x * ??;
}
```

Integer Hole

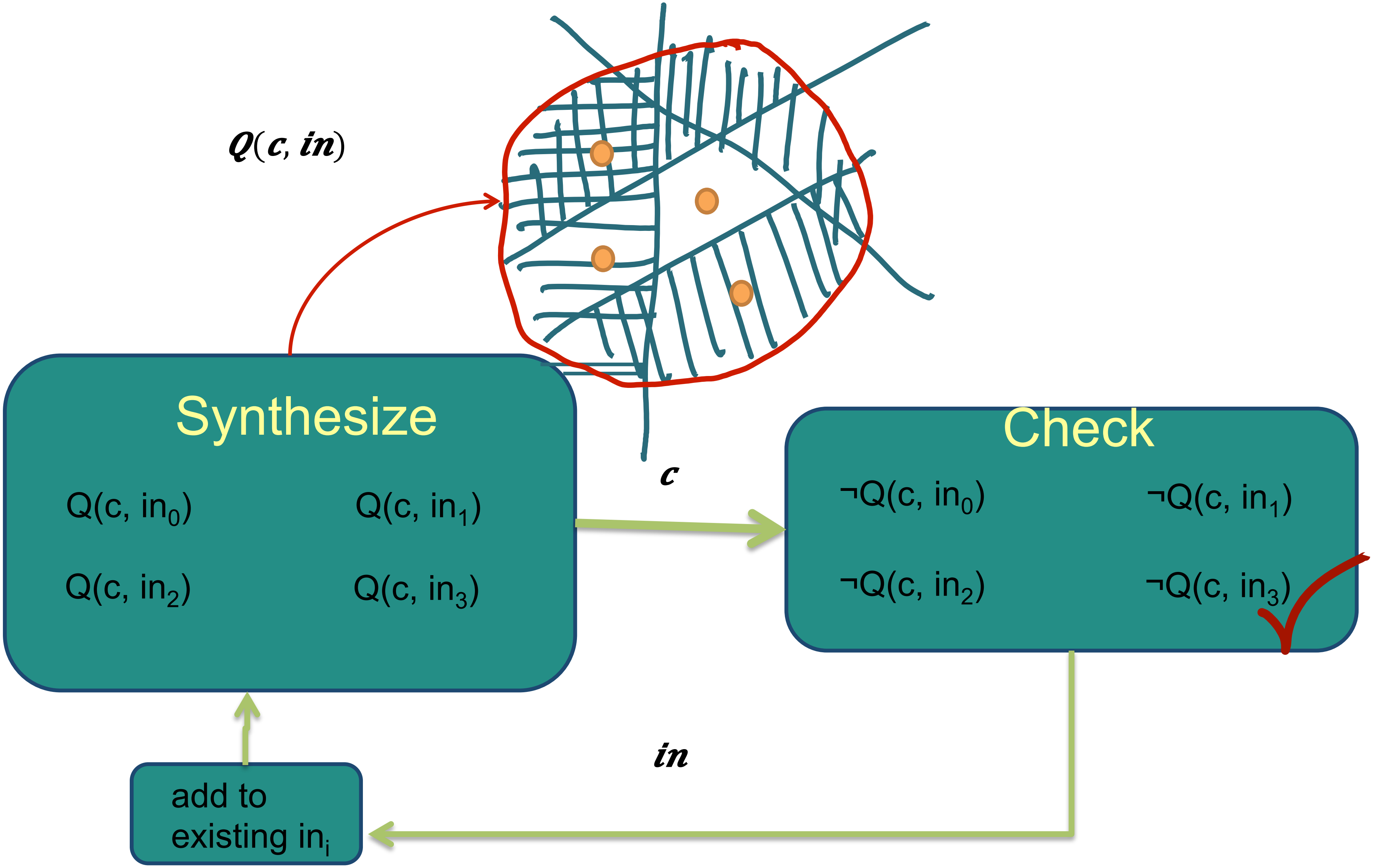
Solving inductive synthesis



This is known as **CEGIS**

(Counter-Example Guided Inductive Synthesis)

CEGIS in Detail



Synthesizing function bodies

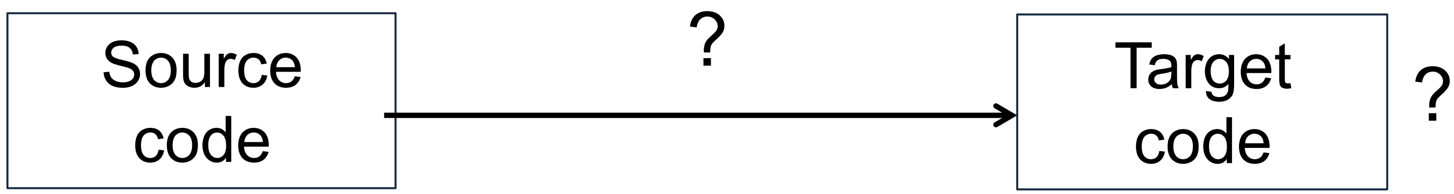
- Model each possible function using minterms
- Choose among candidates using multiplexers
- Example:

```
int c = ??;
if (c == 0) return foo();
else if (c == 1) return bar();
else if (c == 2) return baz();
else error;
```

- Can now use CEGIS as before to find value of ??

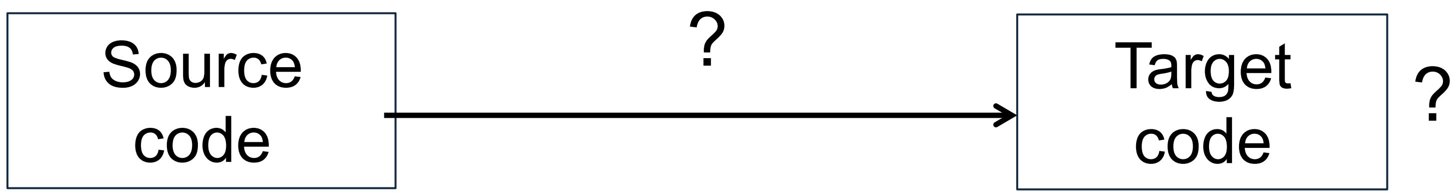
What does any of this has to do with compilers?

Recall from last lecture



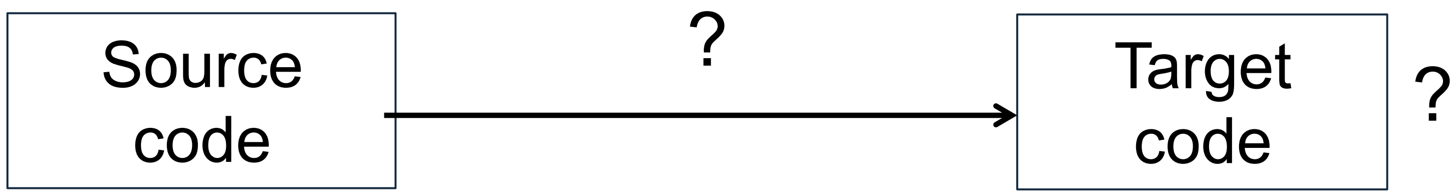
- Source and target languages have well-specified semantics
  - Otherwise we don't know what we are doing
- We need to do two things:
  - *Find* code written in target language to convert source into
  - *Verify* that the found fragment is correct, i.e., semantic-preserving

Recall from last lecture



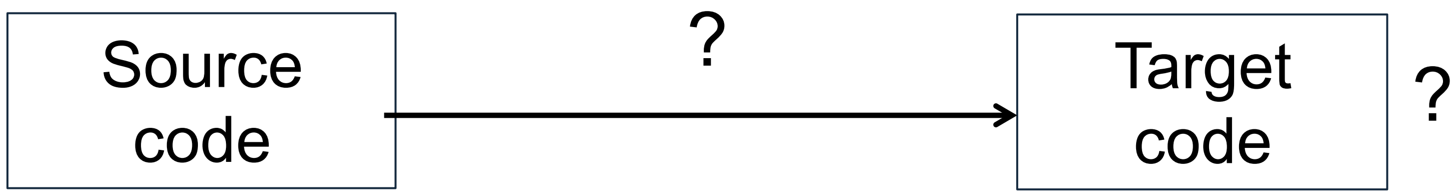
- Traditional compilers solve this using semantic-preserving transformation passes
  - Or so you hope
- Superoptimizers solve this using targeted search
  - Treat source code as specification
  - Still need to axiomatize possible transforms

Recall from last lecture



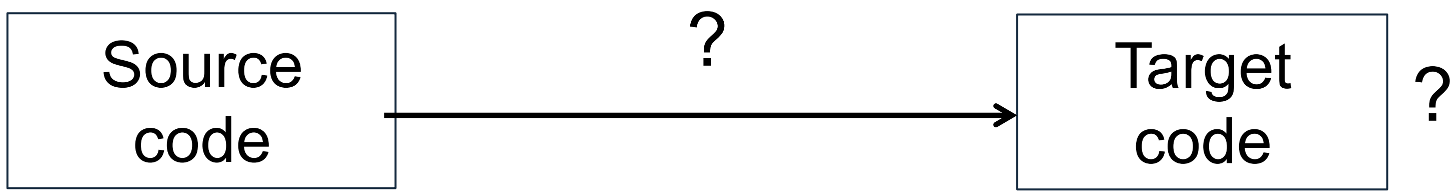
- Insight 1: given a target code fragment, we can check whether it satisfies spec or not
  - At least semi-automatically, cf. HW2
- Insight 2: we can generate candidate source-target code fragments and use verifier to check its validity
  - This is now an inductive synthesis problem!
  - We search for *both* target code and proof

Recall from last lecture



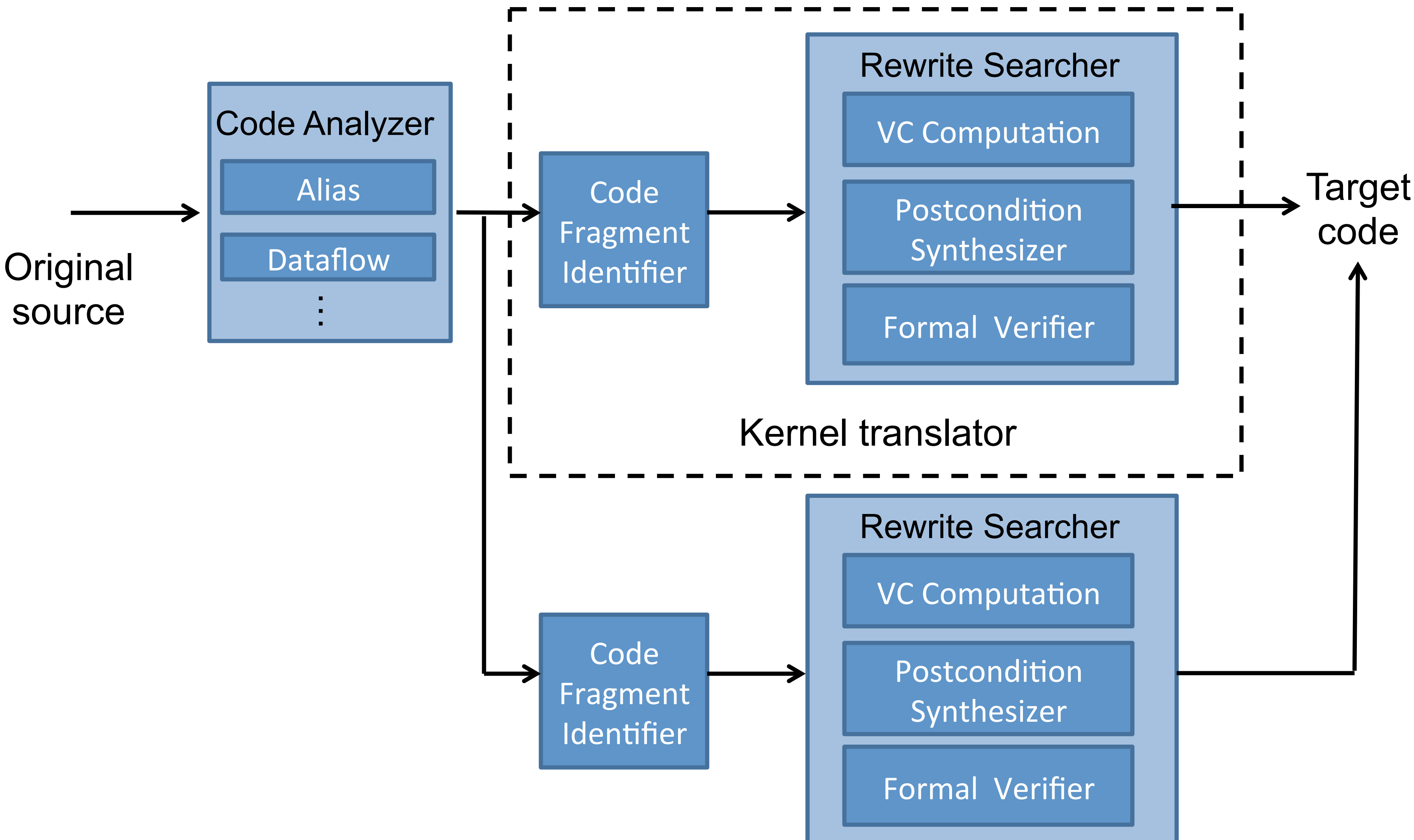
- Issue 1: searching for target code fragments given concrete syntax is very expensive
  – Translate from x86 assembly to SPARC
- Issue 2: Hoare-style verification requires finding loop invariants
  – Problem is undecidable in general

Recall from last lecture

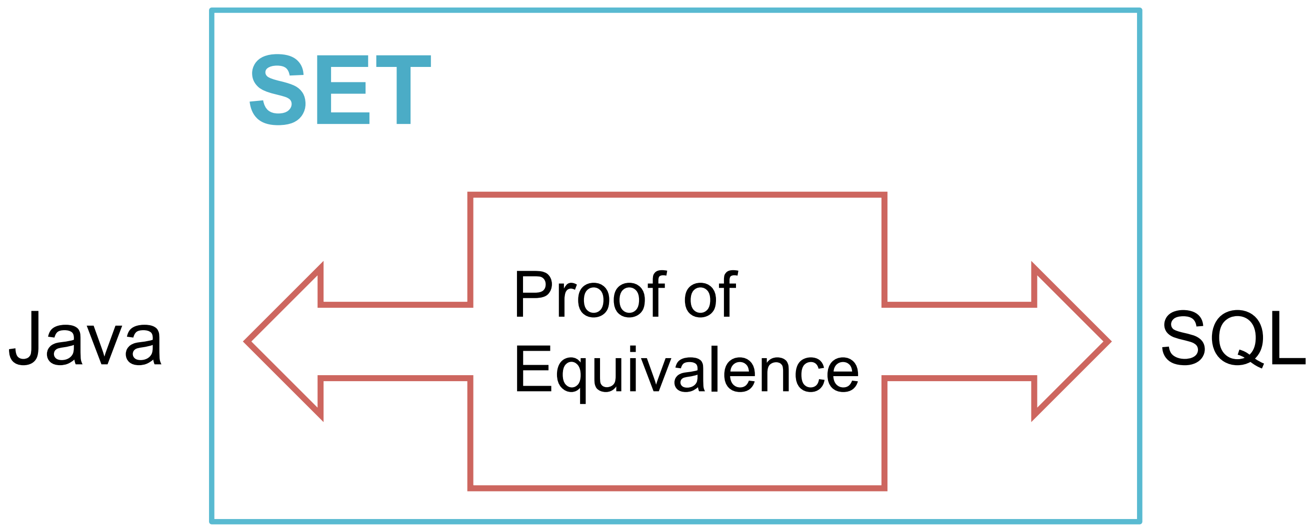


- Issue 1: searching for target code fragments given concrete syntax is very expensive
  - We first "lift" source code to a higher level representation before searching
- Issue 2: Hoare-style verification requires finding loop invariants
  - We only need to find invariants that is "strong enough" to validate the postconditions

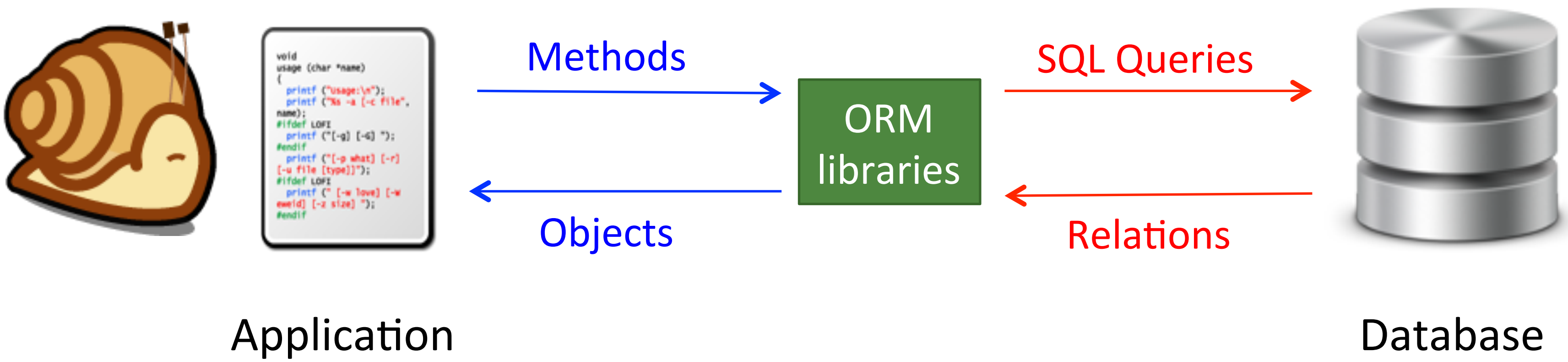
Synthesis-Enabled Translation



Kernel Translator #1: Java to SQL



Kernel Translator #1: Java to SQL



Java to SQL

```
List getUsersWithRoles () {
  List users = User.getAllUsers();
  List roles = Role.getAllRoles();
  List results = new ArrayList();
  for (User u : users) {
    for (Role r : roles) {
        if (u.roleId == r.id)
           results.add(u); }}
  return results; }
```

```
SELECT * FROM user
```

```
SELECT * FROM role
```

convert
to

```
List getUsersWithRoles () {
 return executeQuery(
  “SELECT   u FROM user u, role r
    WHERE    u.roleId == r.id
    ORDER BY u.roleId, r.id”;
}
```

Java to SQL

```
List getUsersWithRoles () {
  List users = User.getAllUsers();
  List roles = Role.getAllRoles();
  List results = new ArrayList();
  for (User u : users) {
    for (Role r : roles) {
        if (u.roleId == r.id)
          results.add(u); }}
  return results; }
```

```
outerInvariant(users, roles,
       u, results, …)
```

```
innerInvariant(users, roles,
      u, r, results, …)
```

```
results = outputExpr(users, roles)
```

Verification conditions

precondition →
  outerInvariant(users/query(…), results/[], …)

outerInvariant(…) ⋀ outer loop terminates →
  results = outputExpr(users, roles) …

Expressing invariants

- Theory of Ordered Relations (TOR)
- Similar to relational algebra
- Model relations as ordered lists

L := program var
  | []
  | L : L | L : e
  | $top_e(L)$
  | $L \bowtie_f L$ | $\sigma_f(L)$
  | $\pi_f(L)$ | $order_e(L)$

e := L[i]
  | e *op* e
  | max(L) | min(L)
  | sum(L) | avg(L)
  | size(L)

Java to SQL

```
List getUsersWithRoles () {
  List users = User.getAllUsers();
  List roles = Role.getAllRoles();
  List results = new ArrayList();
  for (User u : users) {
    for (Role r : roles) {
        if (u.roleId == r.id)
           results.add(u); }}
  return results; }
```

outerInvariant(users, roles, u, results, …)

$results_{j+1} = results_j : users[i] \bowtie_{roleId = id} roles [0..j]$

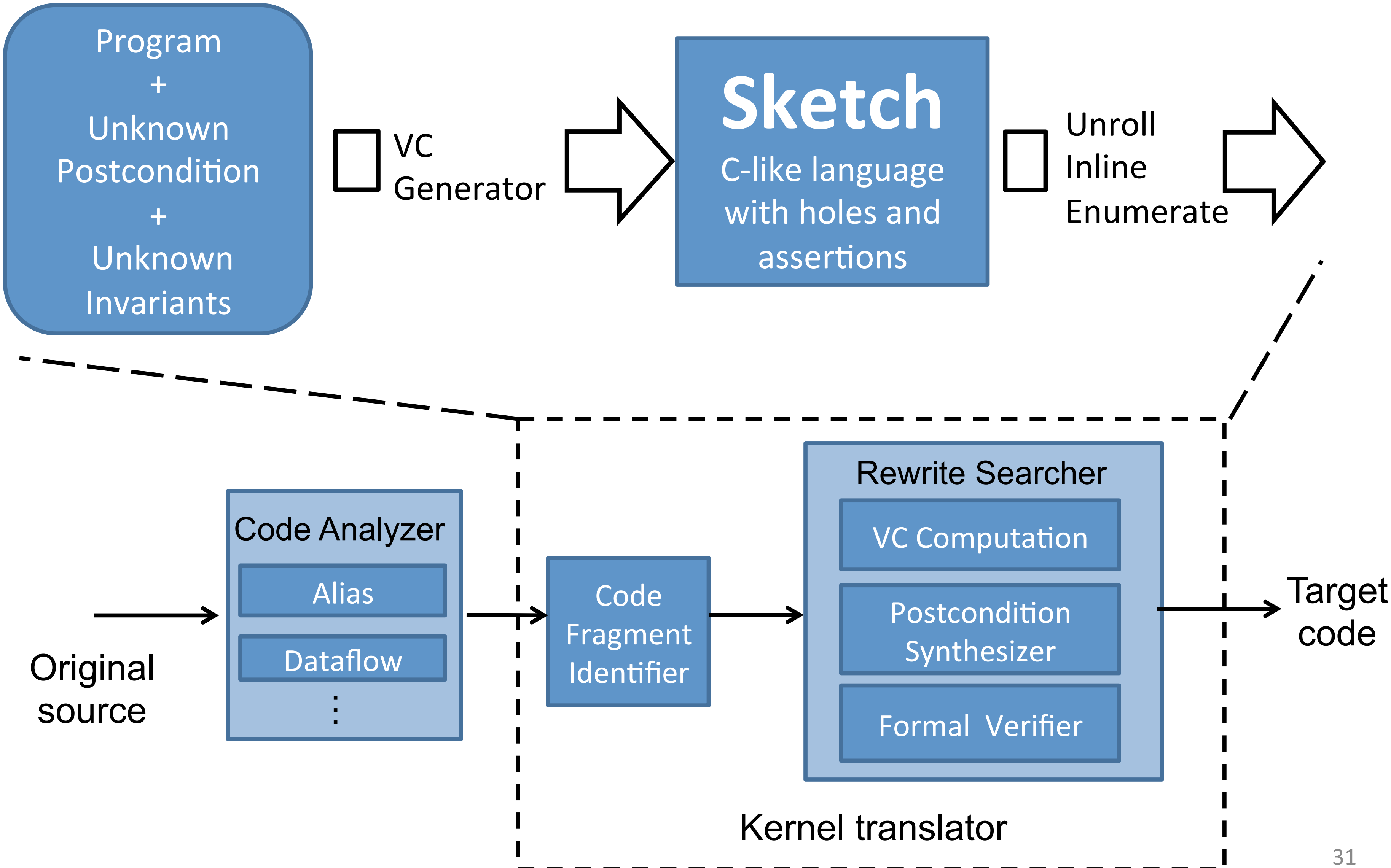
$results = users \bowtie_{roleId = id} roles$

Verification conditions

precondition →
outerInvariant(users/query(…), results/[], …)

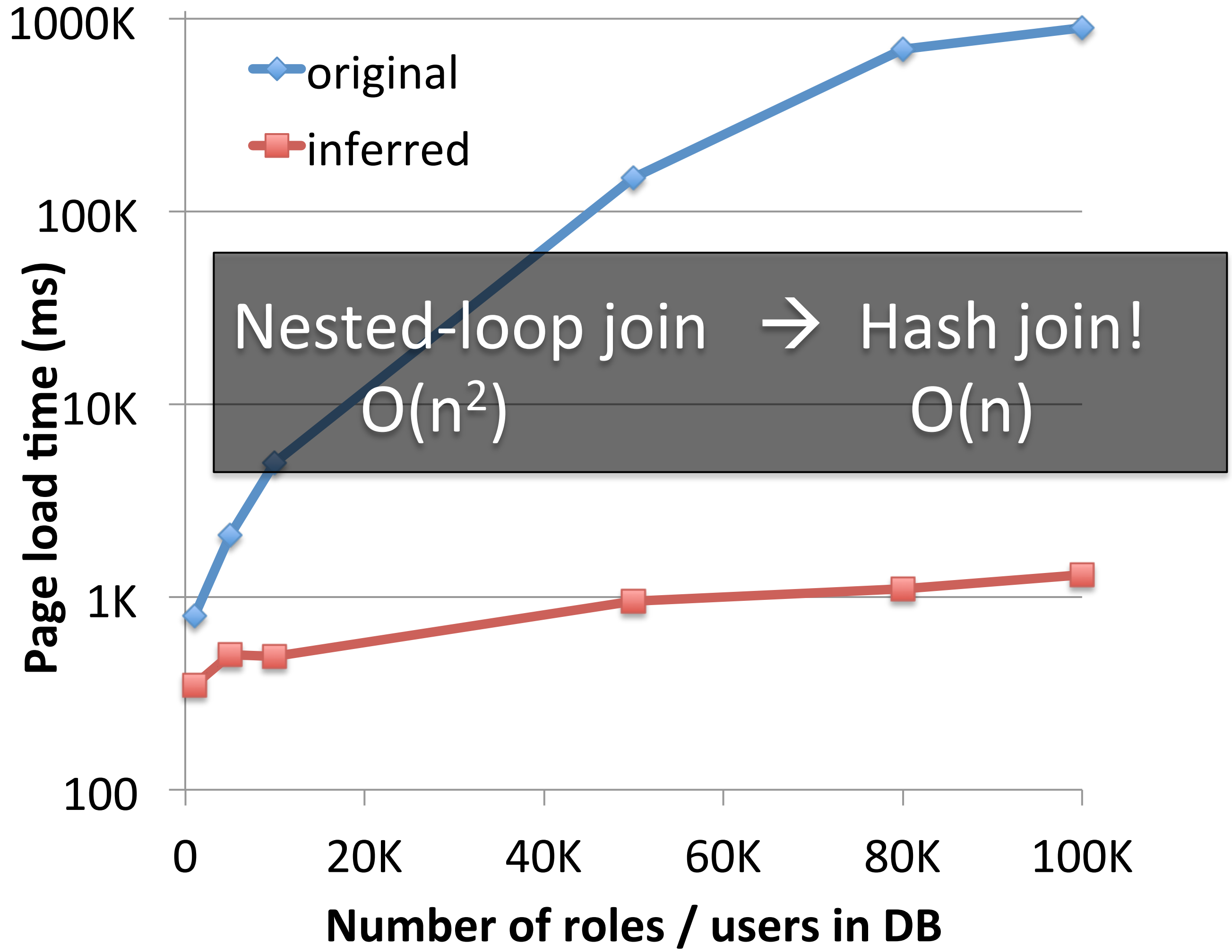
outerInvariant(…) ∧ outer loop terminates →
results = outputExpr(users, roles) …

Java to SQL



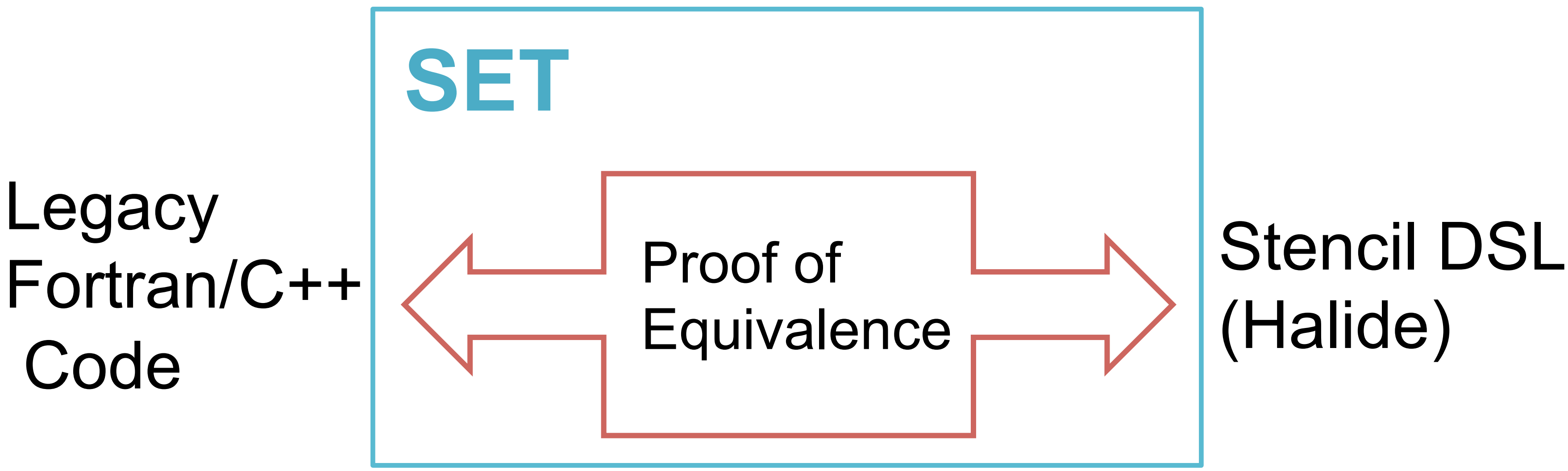
Program
+
Unknown
Postcondition
+
Unknown
Invariants
VC
Generator
Sketch
C-like language
with holes and
assertions
Unroll
Inline
Enumerate
Original
source
Code Analyzer
Alias
Dataflow
Code
Fragment
Identifier
Rewrite Searcher
VC Computation
Postcondition
Synthesizer
Formal Verifier
Target
code
Kernel translator

Join Query



1000K
100K
10K
1K
100
Page load time (ms)
original
inferred
Nested-loop join → Hash join!
O(n²)
O(n)
0
20K
40K
60K
80K
100K
Number of roles / users in DB

Kernel Translator #2: Fortran to Halide



Legacy Fortran to Halide

```
for (k=y_min-2;k<=y_max+2;k++) {
   for (j=x_min-2;j<=x_max+2;j++) {
      post_vol[((x_max+5)*(k-(y_min-2))+(j)-(x_min-2))]
        = volume[((x_max+4)*(k-(y_min-2))+(j)-(x_min-2))]
          + vol_flux_y[((x_max+4)*(k+1 -(y_min-2))+(j)-
                        (x_min-2))]
          - vol_flux_y[((x_max+4)*(k-(y_min-2))+(j) −
                        (x_min-2))];
   }
}
```

Postcondition:

```
post_vol[j,k] = volume[j,k] + vol_flux[j,k+1] + vol_flux[j,k]
```

Expressing invariants

$$\forall (i, j) \in Dom . A[i, j] = expr(\{B_n[expr(i,j), expr(i,j)] \})$$

```
out = 0;
for(int i=0; i<n-1; ++i){
     out[i+1] = in[i];
}
```

$0 \leq i \leq n-1$
$\forall j \in [1,i] \;\; out[j] = in[j-1]$
$\forall j \notin [1,i] \;\; out[i] = 0$

Loop invariant

- Big invariants
- Complex floating point arithmetic
- Universal Quantifiers

Example

```
out = 0
for(int i=0; i<n-1; ++i){
      out[i+1] = in[i];
}
```

$$\forall\, i, n, out, in, idx \quad \begin{matrix} 0 \le i \le n-1 \\ \forall j \in [1,i]\ out[j] = in[j-1] \\ \forall j \notin [1,i]\ out[i] = 0 \end{matrix} \ \wedge\ i \ge n-1 \ \rightarrow \text{out[idx]} = \begin{cases} \text{in[idx]} & \text{idx} \in [1,\text{n}) \\ 0 & \text{otherwise} \end{cases}$$

Loop invariant ¬loopCond $out = expr$

Example

```
out = 0
for(int i=0; i<n-1; ++i){
      out[i+1] = in[i];
}
```

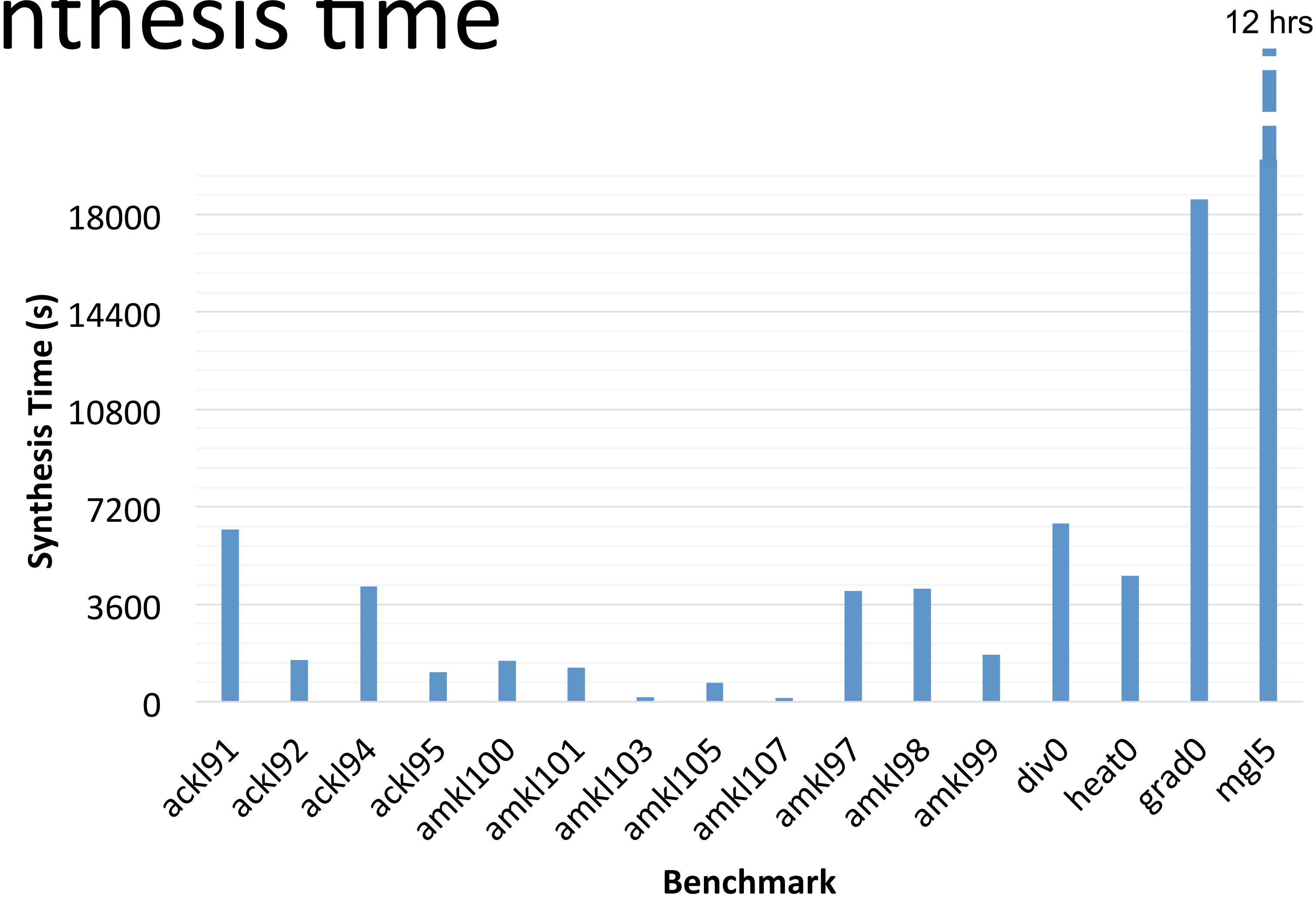
$$\forall\ i, n, out, in, idx\ \left(0 \le i \le n-1 \;\; \bigwedge_{j\in\{idx\}\cap[1,i]} out[j] = in[j-1] \;\; \bigwedge_{j\in\{idx\}\cap\overline{[1,i]}} out[j] = 0\right) \wedge\ i \geq n-1 \ \rightarrow out[idx] = \begin{cases} in[idx] & idx \in [1,n) \\ 0 & \text{otherwise} \end{cases}$$

Loop invariant

$\neg$loopCond

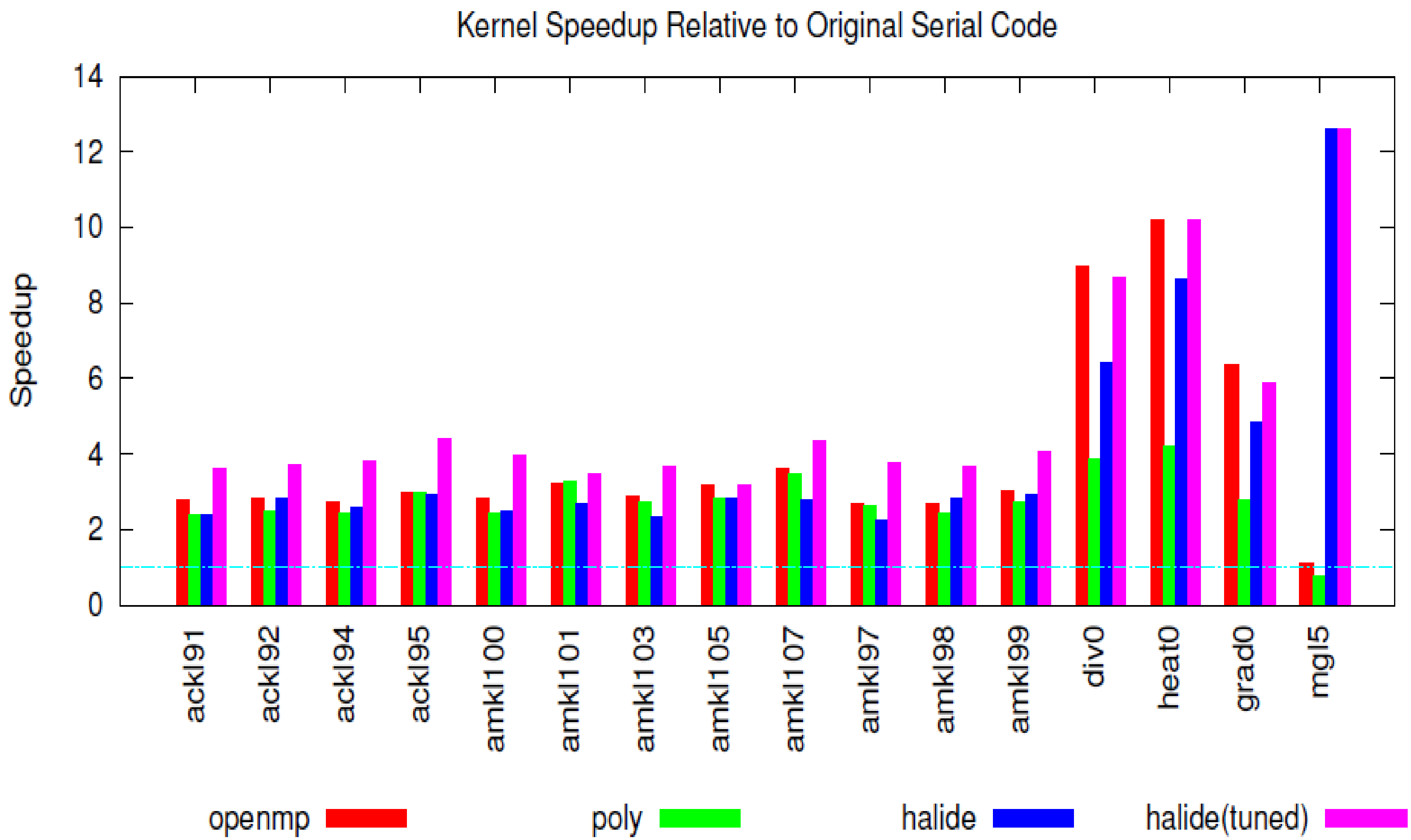
$out = expr$

Synthesis time



Synthesis time with parallel synthesis on 24 cores

Speedups



Speedups on 24 cores

Summary

- Automatic translation from source to target language is hard
- Use synthesis to bridge the gap

- Future work:
  - Cost-based translation
  - Language for developers to express invariants

Course Outline

- Static analysis
- Language design
- Program Verification
- Dynamic analysis
- New compilers
  - superoptimizers
  - synthesis-based translation

Other PL classes of interest

- 503: Software Engineering
- 505: Programming Languages
- 507: Computer-Aided Reasoning for Software
- 504: Advanced Topics in Software Systems
- 599: Verifying Software Systems

Thank you for taking this class
Have a great summer!