Software Synthesis and Automated Reasoning
Who

• Instructor
  ‣ Shachar Itzhaky  shachari@cs.technion.ac.il

• TA
  ‣ Eytan Singher  eytan.s@cs.technion.ac.il
Structure of Lectures

Traditional Classroom

Blah blah boring stuff

Flipped Classroom

Semi-Flipped Classroom

How did the pig's paw-prints get on the ceiling?
Structure of Lectures

• 50 min lecture + 50 min class assignments
  ▸ Work in pairs (recommended)
  ▸ Have a laptop
  ▸ **Pre-install** required software
    ○ Either use supplied VM (easy) or install locally (harder)
  ▸ Not part of final grade
Structure of Grade

40%  
Homework Assignments  
O(3)  
Programming problems  
In pairs  
Small

60%  
Final Project  
Application of Sketch  
(with the help of TA)  
In pairs  
Medium
**Reading List**

- **Textbooks**
  - “Formal Reasoning About Programs” / Adam Chlipala
  - “Software Foundations” volumes 1, 2 / Benjamin C. Pierce

- **Papers**
  - (for specific topics during 2\textsuperscript{nd} half of term)
Automated Formal Reasoning

• What is reasoning?

Every person has secrets.

Angelina Jolie is a person.

Angelina Jolie has secrets.
Automated Formal Reasoning

• What is formal reasoning?
הכניסה לתיות אבודת בלבד!
كيفי הבטוחים

10
ישם לב: במкерר זו יתרבע ניקיון בכל יום ראשון.
הנכם מחבקיםلفנות.Marax! 묵רים לא חחושים벤ומ ביתך לפק! 
תודה רבה.
יינב איבוטבול.
That which is left unsaid

I attended a class at MIT and most of the students were Asian.
Reasoning: Formalism

• Zermelo’s Theorem
  ‣ In Chess, either White can force a win, or Black can force a win, or both sides can force a draw.

What we need is a formalism.
Reasoning: First-order Logic

• In every (non-empty) bar, there is one person such that if he (she) drinks, then everybody drinks.

\[ \exists x. \text{drinks}(x) \to \forall y. \text{drinks}(y) \]

• In every (non-empty) set of natural numbers there is a minimal element.

\[ \exists n \in S. \forall m \in S. n \leq m \]
Reasoning: Second-order Logic

• Every real number is the supremum (least upper bound) of some set of rational numbers.

\[ \forall r \in \mathbb{R}. \exists S \subseteq \mathbb{Q}. r = \sup S \]

*Where (definition of sup)*

\[ \forall S. \quad \forall x \in \mathbb{Q}. x \in S \rightarrow x \leq \sup S \]

\[ \land \]

\[ \forall y \in \mathbb{R}. (\forall x \in \mathbb{Q}. x \in S \rightarrow x \leq y) \rightarrow \sup S \leq y \]
Reasoning: Proofs

• What is a proof?

A proof is a description that we can read and be convinced, beyond any doubt, that a statement is correct.

A proof is a document whose consistency can be checked mechanically, (via an algorithm) to validate its conclusion.
Reasoning: Proofs

• Modus Ponens

\[
\begin{array}{c}
\vdash A \\
\vdash A \rightarrow B \\
\hline
\vdash B
\end{array}
\]

(MP)

• Proof calculi:
  - Hilbert, Natural Deduction, Sequent Calculus, ...

A proof is a mathematical object.
Automated Reasoning

Proof Checker
validates logical consequence
(small trusted core)

Theorem Prover
proof search
exhaustive (heuristic)

Proof Assistant
automates tedious mechanics
of writing proofs

Solver
constructs a model for a
formula, or declares none
Reasoning About Programs

• Euclid’s algorithm

```python
# a, b > 0
while a != b:
    if a < b:
        b = b - a
    else:
        a = a - b

output a = gcd(input a, input b)
```
Programming Language Semantics

• WHILE language
  
  ▸ Syntax:

  $$S \rightarrow x := E | S ; S | \text{skip}$$
  $$\text{if } E \text{ then } S \text{ else } S$$
  $$\text{while } E \text{ do } S$$

  $$E \rightarrow x | # | E \circ E$$

  $$\circ \in \{+, -, *, /, =, \neq, <, >, \leq, \geq\}$$
Semantics: Program States

euclid =

# a, b > 0
while a ≠ b do
  if a < b then
    b := b - a
  else
    a := a - b

values of program variables
Semantics: Expressions

• $\sigma : \text{Var} \rightarrow \mathbb{Z}$
  
  ‣ A store — assigns one value per variable

• $\Sigma$ — the set of all such stores

• $\llbracket e \rrbracket : \Sigma \rightarrow \mathbb{Z}$
  
  ‣ $\llbracket e \rrbracket_\sigma$ is the value of $e$ when interpreted in state $\sigma$

$$\llbracket a - b \rrbracket(\begin{array}{c} a \\ b \end{array}) = 3$$
Semantics: Expressions

Base cases

\[
\begin{align*}
⟦x⟧_\sigma &= σx & (x \in \text{Var}) \\
⟦n⟧_\sigma &= n & (n \in \mathbb{Z})
\end{align*}
\]

Recursive case

\[
⟦e_1 \triangleleft e_2⟧_\sigma = ⟦e_1⟧_\sigma \triangleleft ⟦e_2⟧_\sigma
\]
Structural Operational Semantics

Small-step Semantics

• Define a new relation:

\[ \sigma, c \rightarrow \sigma', c' \]

- running statement \( c \) in state \( \sigma \) results in a new state \( \sigma' \) and a new ("remaining") command \( c' \).
  - \( c' \) serves as program counter

• An execution is a trace:

\[ \langle \sigma, c \rangle \rightarrow \langle \sigma_1, c_1 \rangle \rightarrow \langle \sigma_2, c_2 \rangle \rightarrow \cdots \rightarrow \langle \sigma_n, c_n \rangle \]
Execution Traces — Example

\[
\begin{array}{c|c}
  a & b \\
  \hline
  18 & 15 \\
\end{array}
\]

\[
b := 10;
if a < b then \\
  b := b - a \\
else skip
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  18 & 10 \\
\end{array}
\]

\[
\text{if } a < b \text{ then } \\
  b := b - a \\
\text{else skip}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  8 & 10 \\
\end{array}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  8 & 2 \\
\end{array}
\]

\[
\text{skip}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  18 & 10 \\
\end{array}
\]

\[
\text{if } a < b \text{ then } \\
  b := b - a \\
\text{else skip}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  18 & 10 \\
\end{array}
\]

\[
\text{skip}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  8 & 5 \\
\end{array}
\]

\[
b := 10;
if a < b then \\
  b := b - a \\
else skip
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  8 & 10 \\
\end{array}
\]

\[
\text{if } a < b \text{ then } \\
  b := b - a \\
\text{else skip}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  8 & 2 \\
\end{array}
\]

\[
\text{skip}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  18 & 15 \\
\end{array}
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  \hline
  18 & 10 \\
\end{array}
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\[
\text{skip}
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\text{if } a < b \text{ then } \\
  b := b - a \\
\text{else skip}
\]

\[
\begin{array}{c|c}
  a & b \\
  \hline
  18 & 10 \\
\end{array}
\]

\[
\text{skip}
\]
Structural Operational Semantics

• Rule-based definition of $\rightarrow$:

\[
\sigma, x := e \rightarrow \sigma[x \mapsto \llbracket e \rrbracket \sigma], \text{skip}
\]

- $\sigma, x := e \rightarrow \sigma[x \mapsto \llbracket e \rrbracket \sigma], \text{skip}$
- set value of $x$ to $\llbracket e \rrbracket \sigma$

\[
\sigma, c_1 \rightarrow \sigma', c_1'
\]

\[
\sigma, c_1; c_2 \rightarrow \sigma', c_1'; c_2
\]

\[
\sigma, \text{skip}; c_2 \rightarrow \sigma, c_2
\]
Structural Operational Semantics

\[
\begin{align*}
[e]_\sigma &\neq 0 \\
\sigma, \text{if } e \text{ then } c_1 \text{ else } c_2 &\rightarrow \sigma, c_1 \\
[e]_\sigma &\neq 0 \\
\sigma, \text{while } e \text{ do } c &\rightarrow \sigma, \text{while } e \text{ do } c \\
[e]_\sigma &\neq 0 \\
\sigma, \text{while } e \text{ do } c &\rightarrow \sigma, \text{skip}
\end{align*}
\]
Properties of a Semantics

- **Theorem.** (*determinism*)
  If $\sigma, c \rightarrow^* \sigma'_1, \text{skip}$ and $\sigma, c \rightarrow^* \sigma'_2, \text{skip}$
  then $\sigma'_1 = \sigma'_2$.

- **Proof.** By induction on the length of the derivation.
  Notice that for a given $c$, at most one derivation rule may match.
Semantic Properties: euclid

• **Proposition**: the following program outputs positive values (subject to the input condition).

```
# a, b > 0
while a ≠ b do
  if a < b then
    b := b - a
  else
    a := a - b
```

\[\sigma a > 0 \land \sigma b > 0 \land \sigma, \text{euclid} \rightarrow^* \sigma', \text{skip}\]

\[\Rightarrow (\sigma'a > 0 \land \sigma'b > 0)\]
Semantic Properties: euclid

• **Proof**: by loop invariant

\[
I \triangleq (\sigma a > 0 \land \sigma b > 0)
\]

\[
\sigma, \text{euclid} \rightarrow^* \sigma', \text{skip}
\]

\[
\Rightarrow (\sigma'a > 0 \land \sigma'b > 0)
\]
Semantic Properties: euclid

• **Proposition:** the following program **terminates** (subject to the input condition).

\[
\begin{align*}
\text{euclid} &= \quad \# \text{ a,b > 0} \\
&\quad \text{while } a \neq b \text{ do} \\
&\quad \quad \text{if } a < b \text{ then} \\
&\quad \quad \quad b := b - a \\
&\quad \quad \text{else} \\
&\quad \quad \quad a := a - b \\
\end{align*}
\]

\[(\sigma a > 0 \land \sigma b > 0) \Rightarrow \exists \sigma'. \sigma, \text{euclid } \rightarrow^* \sigma', \text{skip}\]
Semantic Properties: euclid

\[(\sigma a > 0 \land \sigma b > 0) \Rightarrow \exists \sigma'. \sigma, \text{euclid} \rightarrow^* \sigma', \text{skip} \]

- **Proof**: by well-founded induction on states by the order relation \(<\) defined as —

\[\sigma_1 < \sigma_2 \triangleq (\sigma_1 a < \sigma_2 a \land \sigma_1 b \leq \sigma_2 b) \lor (\sigma_1 a \leq \sigma_2 a \land \sigma_1 b < \sigma_2 b)\]

\begin{align*}
\text{# } a, b > 0 \\
\text{while } a \neq b \text{ do} \\
\text{if } a < b \text{ then} \\
\quad b := b - a \\
\text{else} \\
\quad a := a - b
\end{align*}
Variants of Operations Semantics

• Big-step semantics: \( \sigma, c \Downarrow \sigma' \)
  ‣ Also called “natural semantics”

• Small-step semantics for expressions
  ‣ When is it useful..?
Now, for the good stuff
What is Software Synthesis?

IBM, 1957

The FORTRAN Automatic Coding System

J. W. BACKUS†, R. J. BEEBER†, S. BEST‡, R. GOLDBERG†, L. M. HAIBT†,
H. L. HERRICK†, R. A. NELSON†, D. SAYRE†, P. B. SHERIDAN†,
H. STERN†, I. ZILLER†, R. A. HUGHES§, AND R. NUTT‖

**INTRODUCTION**

THE FORTRAN project was begun in the summer of 1954. Its purpose was to reduce by a large factor the task of preparing scientific problems for IBM's next large computer, the 704. If it were possible for the 704 to code problems for itself and produce as system is now complete. It has two components: the FORTRAN language, in which programs are written, and the translator or executive routine for the 704 which effects the translation of FORTRAN language programs into 704 programs. Descriptions of the FORTRAN language and the translator form the principal
What is Software Synthesis

MIT & NASA, 1957

"Code" (≈165cm)
Modern Software Synthesis

Excel 2013’s coolest new feature that should have been available years ago

Excel Flash Fill Is A Brilliant Time Saver
FlashFill: a feature of Excel 2013

[ Gulwani 2011 ]

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<td>Sven Ottlieb</td>
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Average: 27171  Count: 27  Sum: 27171
FlashFill: a feature of Excel 2013

[Gulwani 2011]

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<td>411 70th Place, Kent, WA, (170) 555-2954, 774-35-2298, 29485</td>
<td>Kent</td>
<td>WA</td>
<td>(170) 555-2954</td>
<td>774-35-2298</td>
<td>29485</td>
</tr>
<tr>
<td>Elizabeth Brown</td>
<td>971 20th Lane, Puyallup, WA, (373) 555-4134, 476-53-7164, 26417</td>
<td>Puyallup</td>
<td>WA</td>
<td>(373) 555-4134</td>
<td>476-53-7164</td>
<td>26417</td>
</tr>
<tr>
<td>Sven Ottlieb</td>
<td>676 17th Lane NE, Renton, WA, (828) 555-1593, 548-73-8633, 27440</td>
<td>Renton</td>
<td>WA</td>
<td>(828) 555-1593</td>
<td>548-73-8633</td>
<td>27440</td>
</tr>
<tr>
<td>Ann Devon</td>
<td>694 53th Place, Kent, WA, (194) 555-8124, 559-74-4016, 22367</td>
<td>Kent</td>
<td>WA</td>
<td>(194) 555-8124</td>
<td>559-74-4016</td>
<td>22367</td>
</tr>
<tr>
<td>Roland Mendel</td>
<td>581 12th Street NW, Kent, WA, (103) 555-2146, 303-79-1328, 20518</td>
<td>Kent</td>
<td>WA</td>
<td>(103) 555-2146</td>
<td>303-79-1328</td>
<td>20518</td>
</tr>
<tr>
<td>Aria Cruz</td>
<td>594 85th Lane, Renton, WA, (431) 555-1376, 329-93-9992, 21498</td>
<td>Renton</td>
<td>WA</td>
<td>(431) 555-1376</td>
<td>329-93-9992</td>
<td>21498</td>
</tr>
<tr>
<td>Diego Roel</td>
<td>550 22th Lane, Renton, WA, (639) 555-6238, 918-34-5172, 25931</td>
<td>Renton</td>
<td>WA</td>
<td>(639) 555-6238</td>
<td>918-34-5172</td>
<td>25931</td>
</tr>
<tr>
<td>Martine Rancé</td>
<td>688 93th Place NW, Kent, WA, (573) 555-3571, 695-94-3479, 22424</td>
<td>Kent</td>
<td>WA</td>
<td>(573) 555-3571</td>
<td>695-94-3479</td>
<td>22424</td>
</tr>
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Modern Software Synthesis: Sketch

[Solar-Lezama 2013]

• Problem: isolate the least significant zero bit in a word
  ‣ example: 0010 1011 → 0000 0100

• Easy to implement with a loop

  ```c
  int W = 32;

  bit[W] isolate0 (bit[W] x) {  // W: word size
    bit[W] ret = 0;
    for (int i = 0; i < W; i++)
      if (!x[i]) { ret[i] = 1; return ret; }
  }
  ```

• Can this be done more efficiently with bitwise operations?
  ‣ Trick: adding 1 to a string of ones turns the next zero to a 1
  ‣ i.e. 000111 + 1 = 001000
/**
 * Generate the set of all bit-vector expressions involving +, &, xor and bitwise negation (~).
 * the bnd param limits the size of the generated expression.
 */

generator bit[W] gen(bit[W] x, int depth) {
    assert depth > 0;
    if (??) return x;
    if (??) return ??;
    if (??) return ~gen(x, depth-1);
    if (??) {
        return { | gen(x, depth-1) (+ | & | ^) gen(x, depth-1) |};
    }
}

Sketch: space of possible implementations
Sketch: synthesis goal

```c
int W = 32;

bit[W] isolate0 (bit[W] x) { ... }

generator bit[W] gen(bit[W] x, int depth) {
    assert depth > 0;
    if (??) return x;
    if (??) return ??;
    if (??) return ~gen(x, depth-1);
    if (??) {
        return { | gen(x, depth-1) (+ | & | ^) gen(x, depth-1) |};
    }
}

bit[W] isolate0sk (bit[W] x) implements isolate0 {
    return gen(x, 3);
}
```
Modern Software Synthesis: Synquid

[Polikarpova et al. 2016]

• Problem: intersection of strictly sorted lists
  › example: [4, 8, 15, 16, 23, 42] [8, 16, 32, 64] → [8, 16]

• Also: we want a guarantee that it’s correct on all inputs — of any size!

๏ Step 1: define a data type for sorted lists

```haskell
data SList e where
  Nil :: SList e
  Cons :: h:e →
    t:SList {v:e | v > h} →
    SList e
```
Synquid: components and synthesis goal

- Step 2: define a set of components
  - Which primitive operations is our function likely to use?
  - Here: \{Nil, Cons, \langle\rangle\}

- Step 3: define synthesis goal as a type

\[
\text{intersect} :: \text{xs:SLList e} \rightarrow \text{ys:SLList e} \rightarrow \\
\{v:SLList e \mid \text{elems } v = \text{elems } xs \cap \text{elems } ys\}
\]
Modern Software Synthesis: SQLizer

[Yaghmazadeh et al. 2017]

Problem: “Find the number of papers in OOPSLA 2010”

Output:

```sql
SELECT count(Publication.pid)
FROM Publication JOIN Conference
    ON Publication.cid = Conference.cid
WHERE Conference.name = "OOPSLA"
    AND Publication.year = 2010
```
What is Software Synthesis?

- Automatic programming?
  - but I have to tell the computer what I want...

level of abstraction

???
Python, Haskell, ...
C
assembly
machine code

Synthesis
= an unusually concise / intuitive programming language
+ a compiler that sometimes doesn’t work 😊
Dimensions in program synthesis

[Gulwani 2010]

Behavioral constraints
how do you tell the system what the program should do?

Structural constraints
what is the space of programs to explore?

Search strategy
How does the system find the program you want?
Behavioral Constraints

• How do you tell the system what the program should do?
  • What is the input language / format?
  • What is the interaction model?
  • What happens when the intent is ambiguous?

Q: What did behavioral constraints look like in FlashFill / Sketch / Synquid / SQLizer?
Behavioral Constraints

For example

- Input/output examples
- Equivalent program
- Formal specifications (pre/post conditions, types, ...)
- Natural language
Structural Constraints

• What is the space of programs to explore?
  • Large enough to contain interesting programs, yet small enough to exclude garbage and enable efficient search
  • Built-in or user defined?
  • Can we extract domain knowledge from existing code?

Q: What did structural constraints look like in FlashFill / Sketch / Synquid / SQLizer?
Structural Constraints

For example

Built-in DSL

User-defined DSL (grammar)
  • + statistical models

User-provided components
  • within straight-line code
  • within recursive functional programs

Languages with synthesis constructs
  • *e.g.* generators in Sketch
Search Strategies

• **Synthesis is search.**
  - Find a program in the space defined by *structural constraints* that satisfies *behavioral constraints*

• **Challenge:** the space is astronomically large
  - The search algorithm is the heart of a synthesis technique

• How does the system find the program you want?
  - How does it know it’s the program you want?
  - How can it leverage structural constraints to guide the search?
  - How can it leverage behavioral constraints to guide the search?
For next week

- **Python**: 3
- **PC**: shachari/Teaching.SSAR
- **Group**