Synthesis
Reading Reflection

Discuss in groups

• If you could express your intent to the computer in any way at all, how would you want to write programs?
  • What input would you have the computer take?
  • How would the interaction between you and the computer work?

• What was confusing about synthesis from the first reading/your understanding of synthesis so far?
  • It’s ok if this is lots of things! We’ll be getting hands-on soon, which should clear up a lot of confusions. :)

• Are there applications that you’d expect are amenable to synthesis but that haven’t made it into the literature yet? (Weren’t mentioned in Chapter 2.)
Reading Key Takeaways

• The core challenges in synthesis:
  • Scalability/size of the program space
  • Capturing user intent—What’s a good spec? How do we get it?
• The variety of plausible specs we can get from users
  • I/O examples, demonstrations, logical specs, natural language, programs with holes, equivalent programs (!)
• The variety of search techniques
  • Enumerative, constraint-based, deductive, statistical
• And at a higher level, the fact that synthesis is not just one technique
• A general sense of the problems to which synthesis has been applied so far
Thank you for your survey answers!
Why synthesis?

There are a few PL techniques that just keep coming up in HCI tasks!
- Program synthesis
- Projection/Structure editors
- Program slicing

Others come up, but these seem to come up all the time.
Demo time
FlashFill

Do you have Excel installed? You can probably run this demo on your own laptop while I run it on mine!
<table>
<thead>
<tr>
<th>Whole Name</th>
<th>Prof. Cheung</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alvin Cheung</td>
<td>Prof. Cheung</td>
</tr>
<tr>
<td>Armando Fox</td>
<td>Prof. Fox</td>
</tr>
<tr>
<td>Jonathan Ragan-Kelley</td>
<td>Prof. Kelley</td>
</tr>
<tr>
<td>Koushik Sen</td>
<td>Prof. Sen</td>
</tr>
<tr>
<td>Sanjit A. Seshia</td>
<td>Prof. Seshia</td>
</tr>
<tr>
<td>Katherine A. Yelick</td>
<td>Prof. Yelick</td>
</tr>
</tbody>
</table>

CTRL + E
Scythe
To run this one, head to: https://scythe.cs.washington.edu/demo
**Example Task:** Find the span of career peak (the year when the first paper and most cited papers are published) of computer scientists given the list of their published papers.

<table>
<thead>
<tr>
<th>author</th>
<th>title</th>
<th>year</th>
<th>citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>H. Simon</td>
<td>Understanding</td>
<td>1974</td>
<td>277</td>
</tr>
<tr>
<td>H. Simon</td>
<td>Organization</td>
<td>1997</td>
<td>20057</td>
</tr>
<tr>
<td>H. Simon</td>
<td>The sciences of</td>
<td>1996</td>
<td>17561</td>
</tr>
<tr>
<td>R. Tibshirani</td>
<td>Developmental re</td>
<td>2004</td>
<td>50</td>
</tr>
<tr>
<td>R. Tibshirani</td>
<td>Flexible discrimin</td>
<td>1995</td>
<td>51</td>
</tr>
<tr>
<td>R. Tibshirani</td>
<td>IRF9 and STAT1</td>
<td>2008</td>
<td>47</td>
</tr>
<tr>
<td>P. Bork</td>
<td>Automated pair</td>
<td>1998</td>
<td>51</td>
</tr>
<tr>
<td>P. Bork</td>
<td>UN targets top kil</td>
<td>2011</td>
<td>19</td>
</tr>
</tbody>
</table>

**Select** `t6.author, t6.min_year, t6.year`  
**From**  
`(Select t5.author, t5.min_year, t4.author As author1, t4.year`  
**From** `(Select t3.author, Min(t3.year) As min_year`  
**From**  
`t3.author) As t5 Join`  
`(Select t7.author, t7.year`  
**From**  
`t7.author, t7.year`  
**And**  
`(Select t1.author, t1.max_citation, t8.author As author1, t8.title, t8.year, t8.citation`  
**From**  
`(Select t2.author, Max(t2.citation) As max_citation`  
**From**  
`t2.author) As t1 Join`  
`papers As t2`  
**Group By**  
`t2.author) As t7`  
**Where**  
`t7.max_citation = t7.citation`  
**And**  
`(t7.author = t7.author1) As t4)`  
**As t6`  
**Where**  
`t6.author = t6.author1;`
Helena

If you want to run this one, you have to install an extension: http://helena-lang.org/install
We open the browser extension.
We demonstrate how to find information that goes in the first row of our target dataset.
We continue on another page (and another table).
We’re done demonstrating.
The synthesizer writes our program.
The program collects our data.
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David S. Johnson
Visiting Professor, Columbia University Computer Science Department
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David Haussler
Scientific Director, UC Santa Cruz Genomics Institute, University of California, Santa Cruz
Verified email at soe.ucsc.edu
genomics  computer science  molecular biology  evolution  cancer

vapnik
I know, I know, not as photogenic, but it makes programs much faster!!

<table>
<thead>
<tr>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td>cmp    r1, #0</td>
<td>asr    r3, r1, #2</td>
</tr>
<tr>
<td>mov    r3, r1, asr #31</td>
<td>add    r2, r1, r3, lsr #29</td>
</tr>
<tr>
<td>add    r2, r1, #7</td>
<td>mov     r3, r3, lsr #29</td>
</tr>
<tr>
<td>mov    r3, r3, lsr #29</td>
<td>movge   r2, r1</td>
</tr>
<tr>
<td>movge  r2, r1</td>
<td>ldrb    r0, [r0, r2, asr #3]</td>
</tr>
<tr>
<td>ldrb   r0, [r0, r2, asr #3]</td>
<td>and     r3, r2, #248</td>
</tr>
<tr>
<td>bic    r1, r2, #248</td>
<td>sub     r3, r1, r3</td>
</tr>
<tr>
<td>sub    r3, r1, r3</td>
<td>asr     r1, r0, r3</td>
</tr>
<tr>
<td>asr    r1, r0, r3</td>
<td>and     r0, r1, #1</td>
</tr>
<tr>
<td>and    r0, r1, #1</td>
<td></td>
</tr>
</tbody>
</table>

Scaling up Superoptimization, Phitchaya Mangpo Phothilimthana
Falx
https://falx.cs.washington.edu/tool
5 min break
Back up. What’s program synthesis?

Find a program $P$ that meets a spec $\phi$(input, output):

$$\exists P. \forall x. \phi(x, P(x))$$

**Correctness Condition**

- **When to use synthesis:**
  - **Ease-of-use/productivity:** When writing $\phi$ is faster or easier than writing $P$
  - **Correctness:** when proving $\phi$ is easier than proving $P$
Hey, I’ve seen this before

I give computer a high-level description of what I want it to do

Computer gives me back a low-level program for doing it
Synthesis vs. compilation

Compilation

Typically deterministic
Typically performs lowering via a sequence of rewrite rules

Synthesis

Searches a space of possible programs
...or sometimes a space of possible sequences of rewrite rules! Look, the line is blurry "(_(ツ)_/"

If it involves search, we usually call it synthesis
Even if you don’t take away anything else from today’s lecture, take away that you can write a synthesizer!
Even if you don’t take away anything else from today’s lecture, take away that you can write a synthesizer!

with...

Enumeration
What do we need to decide to make a synthesizer?

Hint: 3 things

How does the user express what they want the program to do?

What space of programs is the synthesizer allowed to use?

What algorithm will the synthesizer use to search that space?
What do we need to decide to make a synthesizer?

Hint: 3 things

How does the user express what they want the program to do?
Input-Output examples

What space of programs is the synthesizer allowed to use?
Anything in a Domain-Specific Language (DSL) of our choice

What algorithm will the synthesizer use to search that space?
Enumeration
Which is to say...generating programs until we find one that works
Input-Output Examples

• Any work here?

• Nah, this is going to be pretty straightforward.

• Example:

  (\{"x" \to 3, "y" \to 7\}, 23)

  (\{"x" \to 4, "y" \to 4\}, 19)

  (\{"x" \to 2, "y" \to 12\}, 31)

Can you guess it?? Did you already synthesize this in your head?
Domain-Specific Language

- This one’s a classic, but for another domain we might design something more customized

\[
expr := \begin{cases} 
  N \\
  v \\
  (expr + expr) \\
  (expr - expr) \\
  (expr * expr) 
\end{cases}
\]
Spec:
({"x" → 3, "y" → 7}, 23)
({"x" → 4, "y" → 4}, 19)
({"x" → 2, "y" → 12}, 31)

Space of programs:
expr := N
  | v
  | (expr + expr)
  | (expr - expr)
  | (expr * expr)

level 0:
[0, 1, 2, 3, 4, y, x]
count: 7

level 1:
[0, 1, 2, 3, 4, y, x, (0+0), (0*0), (0-0), (0+1), (0*1), (0-1), (0+2), (0*2), (0-2),
(0+3), (0+4), (0-3), (0-4), (0+4), (0-4), (0+y), (0*y), (0-y), (0+y), (0*y), (0-y),
(1+0), (1+1), (1+0), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1),
(1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1),
(2+1), (2+1), (2-1), (2+2), (2+2), (2-2), (2+3), (2+3), (2-3), (2-3), (2+4), (2+4),
(2-4), (2+y), (2*y), (2-y), (2*x), (2*x), (2-x), (3+0), (3+0), (3-0), (3-0), (3+1),
(3+1), (3-1), (3+2), (3+2), (3-2), (3+3), (3+3), (3-3), (3-3), (3+4), (3+4), (3-4),
(3-4), (3+y), (3*y), (3-y), (3*y), (3+x), (3+x), (4+0), (4+0), (4-0), (4-0), (4+1),
(4+1), (4-1), (4-1), (4+2), (4+2), (4-2), (4-2), (4+3), (4+3), (4-3), (4-3), (4+4),
(4+4), (4-4), (4-4), (4+y), (4*y), (4-y), (4+x), (4*x), (4-x), (y+0), (y+0), (y-0),
(y+1), (y+1), (y-1), (y+2), (y+2), (y-2), (y+3), (y+3), (y-3),
(y+4), (y+4), (y-4), (y*y), (y*y), (y-y), (y*x), (y*x), (y-x), (x+0), (x+0), (x-0),
(x+1), (x+1), (x-1), (x+2), (x+2), (x-2), (x+3), (x+3), (x-3), (x+4), (x+4), (x-4),
(x+y), (x*y), (x-y), (x*x), (x*x), (x-x)]
count: 154

level 2:
[0, 1, 2, 3, 4, y, x, (0+0), (0*0), (0-0), (0+1), (0*1), (0-1), (0+2), (0*2),
(0-2), (0+3), (0+4), (0-3), (0-4), (0+4), (0-4), (0+y), (0*y), (0-y), (0+y), (0*y),
(0-y), (1+0), (1+1), (1+0), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1),
(1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1), (1+1),
(1-3), (1+4), (1+4), (1-4), (1+4), (1-4), (1+4), (1-4), (1+4), (1-4), (1+4), (1-4),
(1+4), (1-4), (1+4), (1-4), (1+4), (1-4), (1+4), (1-4), (1+4), (1-4), (1+4), (1-4),
(1-3), (3+2), (3+2), (3-2), (3+3), (3+3), (3-3), (3-3), (3+4), (3+4), (3-4),
(3-4), (3+y), (3*y), (3-y), (3*y), (3+x), (3+x), (4+0), (4+0), (4-0), (4-0), (4+1),
(4+1), (4-1), (4-1), (4+2), (4+2), (4-2), (4-2), (4+3), (4+3), (4-3), (4-3), (4+4),
(4+4), (4-4), (4-4), (4+y), (4*y), (4-y), (4+x), (4*x), (4-x), (y+0), (y+0), (y-0),
(y+1), (y+1), (y-1), (y+2), (y+2), (y-2), (y+3), (y+3), (y-3),
(y+4), (y+4), (y-4), (y*y), (y*y), (y-y), (y*x), (y*x), (y-x), (x+0), (x+0), (x-0),
(x+1), (x+1), (x-1), (x+2), (x+2), (x-2), (x+3), (x+3), (x-3), (x+4), (x+4), (x-4),
(x+y), (x*y), (x-y), (x*x), (x*x), (x-x)]
count: 71,302

Ok, no luck so far. Let's just mash these together! In every possible combination!

Hm, still no luck. Keep mashing.
Enumeration... pruned with Operational Equivalence

Spec:

\[
\begin{align*}
\{ "x" \rightarrow 3, "y" \rightarrow 7 \}, & \quad 23 \\
\{ "x" \rightarrow 4, "y" \rightarrow 4 \}, & \quad 19 \\
\{ "x" \rightarrow 2, "y" \rightarrow 12 \}, & \quad 31
\end{align*}
\]

Space of programs:

\[
\begin{align*}
expr & := N \\
& \mid v \\
& \mid (expr + expr) \\
& \mid (expr - expr) \\
& \mid (expr * expr)
\end{align*}
\]

← Which is the fancy program synthesis way of saying “they do the same thing on the inputs we care about.”

Ok, these are all just 0... which we already have. Why’d you give me these???

And these are the same on all inputs.

And eventually we’ll find some that aren’t the same on all inputs, but are the same on \{"x" \rightarrow 3, "y" \rightarrow 7\}, \{"x" \rightarrow 4, "y" \rightarrow 4\}, and \{"x" \rightarrow 2, "y" \rightarrow 12\}.
This is exactly as simple as it looks. Seriously, you can write this synthesizer in vanilla Python in one page. Let’s see it!
This one isn’t pruning at all.
What do we do to prune with OE?

Just an extra 6 lines!
Pruning based on Operational Equivalence can cut down our search space dramatically!

And this is just at level 2!
So if you’re ever watching a synthesis talk and get confused…just remember enumeration. At a sufficiently high level of abstraction, it’s just going through programs until it finds one that works.
We can make enumeration smarter

• Doesn’t have to be just start with the smallest program, then list all the programs in order of size until you find one that works
• We can have heuristics or language models that let us explore better/likelier programs first instead of smaller programs first
• There are other ways of pruning (other than Operational Equivalence) that let us cut out much more of the space
• We can make smart choices about what constants to include
• This was the easy-to-write version, but there are many ways to make it more effective
  • For a long time, the winner of the SyGuS competition (the primary competition for people who write synthesizers) was an enumerative solver!
  • This is a real technique!
Quick brainstorm. What would you like to synthesize?
Synthesis is like a buffet

- This is not one technique that either applies or doesn’t apply to your problem
- It’s a whole family of techniques
- Tackling a new problem, you’ll probably be looking through a host of existing approaches and tools...
  - If you read synth literature, you’ll see very different domains formalized in very different ways. This isn’t accidental!
  - …and maybe inventing your own. Custom synthesizers are still common
To think about for next reading

• The issue of ambiguous specs. As designers of usable tools, do we want to prevent ambiguous specs? If yes, how? Do we want to allow them? If yes, how does this affect our synthesizer?

• What constrains the design of our target languages for synthesis?

• What’s the tradeoff between designing for making the synthesizer’s task easier vs. designing for the user of the tool?
Please install before next class

https://docs.racket-lang.org/rosette-guide/ch_getting-started.html#%28part._sec~3aget%29

About Rosette

Rosette is a solver-aided programming language that extends Racket with language constructs for program synthesis, verification, and more. To verify or synthesize code, Rosette compiles it to logical constraints solved with off-the-shelf SMT solvers. By combining virtualized access to solvers with Racket's metaprogramming, Rosette makes it easy to develop synthesis and verification tools for new languages. You simply