EECS 598. Program Synthesis: Techniques and Applications

Lecture 2: Syntax-guided synthesis

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Administrivia

- Send paper preference via email by **midnight Sept 4**
- First paper presentation
- First review
- Schedule will be updated with speakers
  - There may be new papers
  - Paper orders may change
  - Check after Sept 5!

Last lecture

High-level intent → **Lower-level code**

Specification —Program synthesis→ Program

- Three pillars: intention, invention, adaptation
- This course: different techniques for different specifications in different applications

Today's lecture

- Syntax-guided synthesis (SyGuS): a framework to study program synthesis
- Programming-by-example (PBE): an instance of SyGuS
- Two PBE techniques: search-based and representation-based

Syntax-guided synthesis

Syntax-guided synthesis (SyGuS)

- SyGuS is a general formulation of program synthesis problems
  - Not a program synthesis technique

- Idea: **search** over **space of programs**
  - Specification $\xrightarrow{\textbf{Search}}$ Program **written according to syntax** (context-free grammar)

    semantic constraint (what should this program do)

    syntactic constraint (what should this program look like)

- Advantages: synthesis becomes more tractable

An example SyGuS problem

- Find a program $f(x)$ in the following grammar

$$e := x \mid 1 \mid e + e$$

such that $f(1) = 2$

syntactic constraint

semantic constraint

- A solution: $f(x) = x + 1$
- Another solution: $f(x) = x + x$

Formal definition of SyGuS

- Given a first-order formula ϕ in a background theory T and a context-free grammar L, the syntax-guided synthesis problem is to find an expression $e \in L$ such that formula $\phi[f/e]$ is valid in theory T.

- In previous example:
  - Find a program in the following grammar, such that $f(1) = 2$

$$e := x \mid 1 \mid e + e$$

first-order formula ϕ

context-free grammar L

  - $x + 1$ is a solution, because $1 + 1 = 2$ is valid in theory of Linear Integer Arithmetic

intuitively, this means $1 + 1 = 2$ is correct

Context-free grammar (CFG)

- CFG defines **syntax** of a programming language
  - A set of programs

- More formally: (T, N, P, S)
  - T: set of terminal symbols
  - N: set of non-terminal symbols
  - P: set of productions of the form $s \rightarrow f(s_1, \cdots, s_n)$
  - $S \in N$: start symbol

An example CFG

- CFG is defined as (T, N, P, S)

  $e := x \mid 1 \mid e + e$

- T: set of terminal symbols

  $\{x,\ 1\}$

- N: set of non-terminal symbols

  $\{e\}$

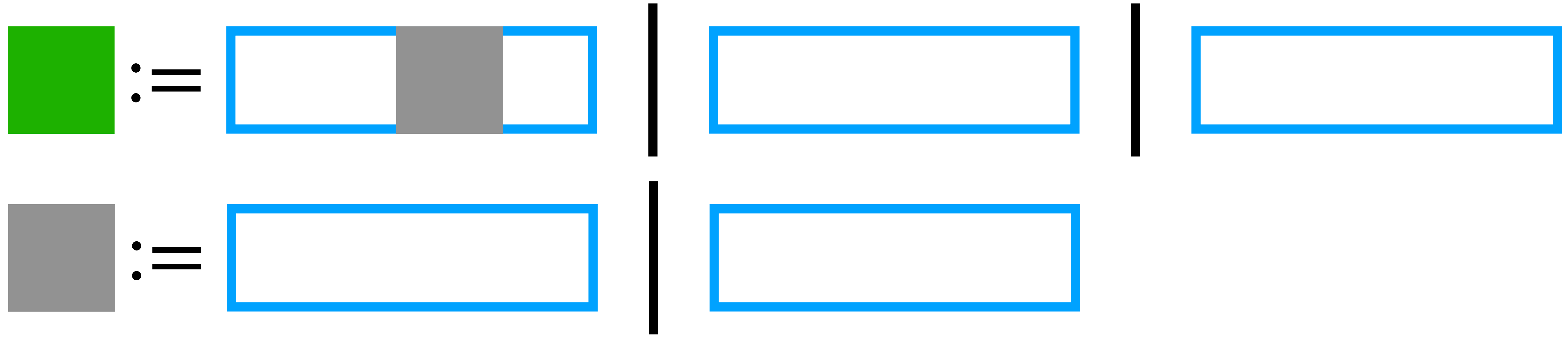
- P: set of productions of the form $s \rightarrow f(s_1, \cdots, s_n)$

  $\{e \rightarrow x,\ e \rightarrow 1,\ e \rightarrow e + e\}$

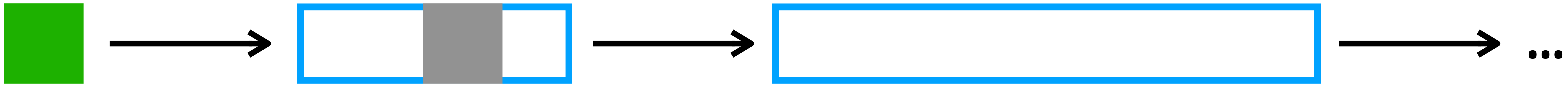
- $S \in N$: start symbol

  e

Write programs according to CFG

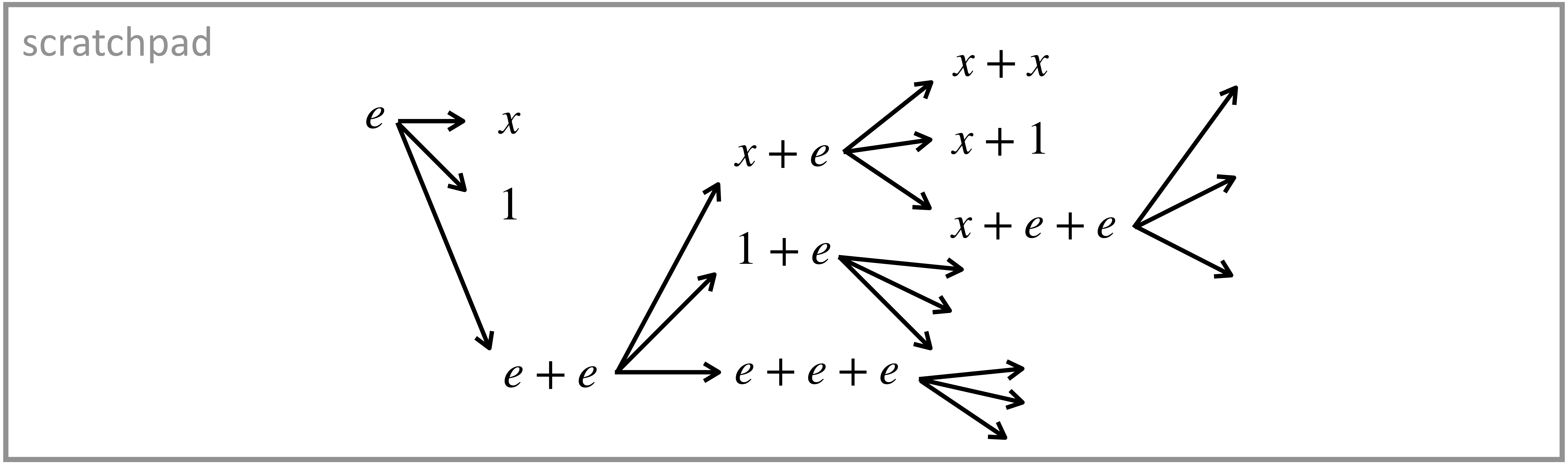


- Step 1: begin with the start symbol
- Step 2: pick a non-terminal in current result and replace it with one of its productions
- Step 3: continue step 2 until no more non-terminal remains (i.e., only terminals)



An example

- CFG: $e := x \mid 1 \mid e + e$



- Step 1: begin with the start symbol
- Step 2: pick a non-terminal in current result and replace it with one of its productions
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SyGuS recap

- Given a first-order formula ϕ in a background theory T and a context-free grammar L, the syntax-guided synthesis problem is to find an expression $e \in L$ such that formula $\phi[f/e]$ is valid in theory T.

SyGuS: $< T, \phi, L >$

Theory:

What does a program mean

Specification:

What program we want

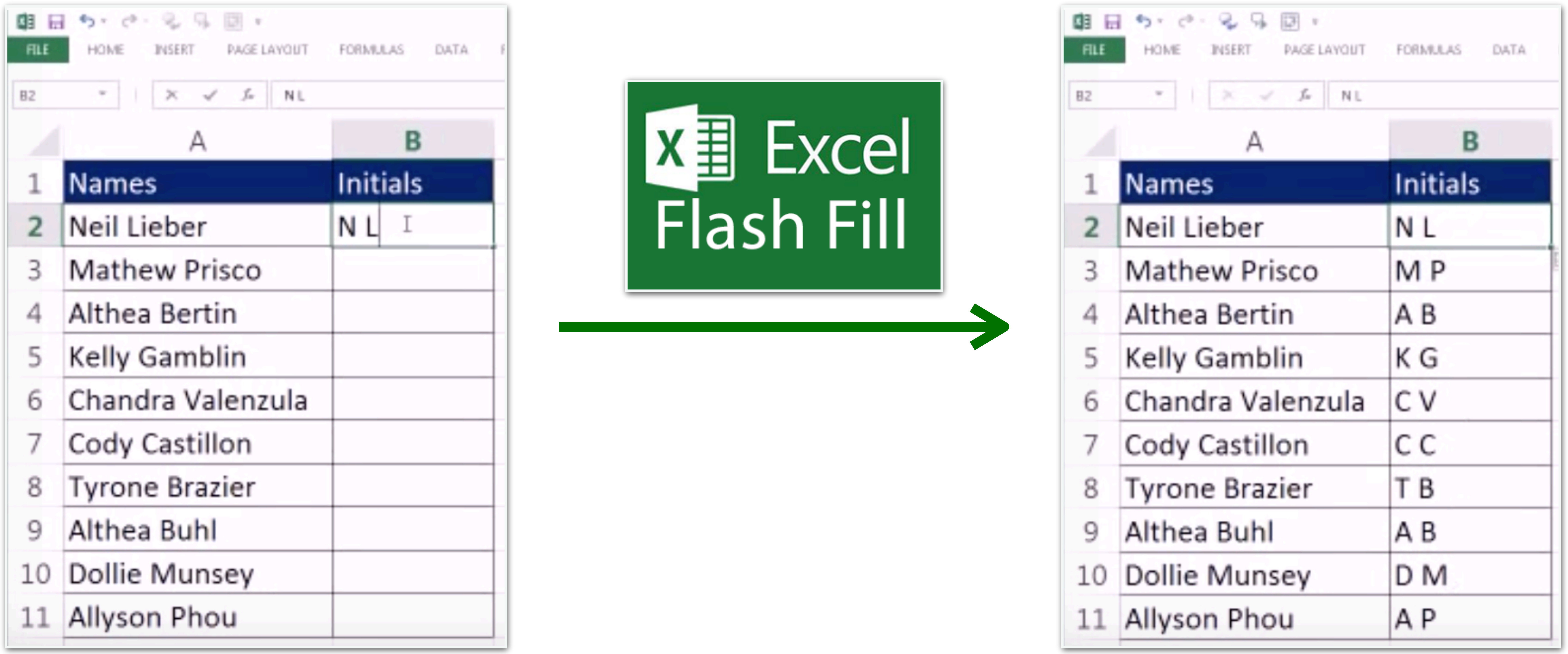
Grammar:

What programs we consider

Programming-by-Example

Programming-by-example (PBE)

- PBE is a specific kind of SyGuS
  - Specification ϕ encodes a set of input-output examples
  - Goal of PBE: find a program in CFG that satisfies a given set of I/O examples
  - A more ambitious goal: not only satisfy examples, but actual intent (mind reading!)
  - E.g., FlashFill



Why is PBE important

- Simplest kind of specification (arguably)

- Useful in practice
  - Even non-programmers can provide examples

- Technically fundamental
  - Underly many program synthesis techniques using other specs
  - Will cover these techniques in Module 2 (and Module 3)

Challenges of PBE

- Scalability
  - Search space defined by syntax is huge (although examples are simple)
  - How to find a program w/o waiting too long?
- Ambiguity
  - Examples are ambiguous
  - How to guess the right program w/o one telling you everything about it?
- Usability — how to make PBE systems useful and usable in practice?
- Applicability — how to create PBE systems widely applicable to many domains?
- …

An example PBE problem

- Syntax

e := f | **concat**(f, e)

f := s | **substr**(x, p, p)

p := k | **position**(x, r, k)

r := t | **seq**(t, …, t)

t := <num> | <let> | <ws> | <any> | …

s is string constant, k is int constant,

x is input variable

- Semantics

- Specification

“Bill Gates” —> “BG”

Some sample programs in this language:

concat(“a”, “b”)

“12ab” —> ???

concat(“a”, **substr**(x, 0, 1))

“12ab” —> ???

concat(“a”, **substr**(x, 0, **position**(x, <num>, 1))

“12ab” —> ???

concat(**substr**(x, 0, 1),
substr(x, **position**(x, <ws>, 1), **position**(x, <cap>, 2)))

What does this program do?

Solve PBE problems

- “Bill Gates” —> “BG”

e := f | **concat**(f, e)

f := s | **substr**(x, p, p)

p := k | **position**(x, r, k)

r := t | **seq**(t, …, t)

t := <num> | <let> | <ws> | <any> | …

“Bill Gates”

0 1 4 5 6

- Solution:

“B”

⟦ **concat**(**substr**(x, 0, 1), **substr**(x, **position**(x, <ws>, 1), **position**(x, <cap>, 2))) ⟧ = “BG”

“Bill Gates”

5

Solve PBE problems (cont'd)

- "Bill Gates" —> "BG"
  - Given solution, simple to check correctness
  - … but we do not have solution a priori (only spec!)
  - How to find the solution?

e := f | **concat**(f, e)

f := s | **substr**(x, p, p)

p := k | **position**(x, r, k)

r := t | **seq**(t, …, t)

t := <num> | <let> | <ws> | <any> | …

PBE challenges

- Huge search space (easily $>10^{20}$ in simplified FlashFill language!) — how to scale?

e := f | **concat**(f, e)

f := s | **substr**(x, p, p)

p := k | **position**(x, r, k)

r := t | **seq**(t, …, t)

t := <num> | <let> | <ws> | <any> | …

- Ambiguity — how to find the desired program w/o too many examples?

concat(**substr**(x, 0, 1), **substr**(x, **position**(x, <ws>, 1), **position**(x, <cap>, 2)))

concat(**substr**(x, 0, 1), **substr**(x, 5, 6)))

concat("B", "G")

concat("B", **substr**(x, **position**(x, <ws>, 1), **position**(x, <cap>, 2)))

…

PBE techniques

Many PBE techniques

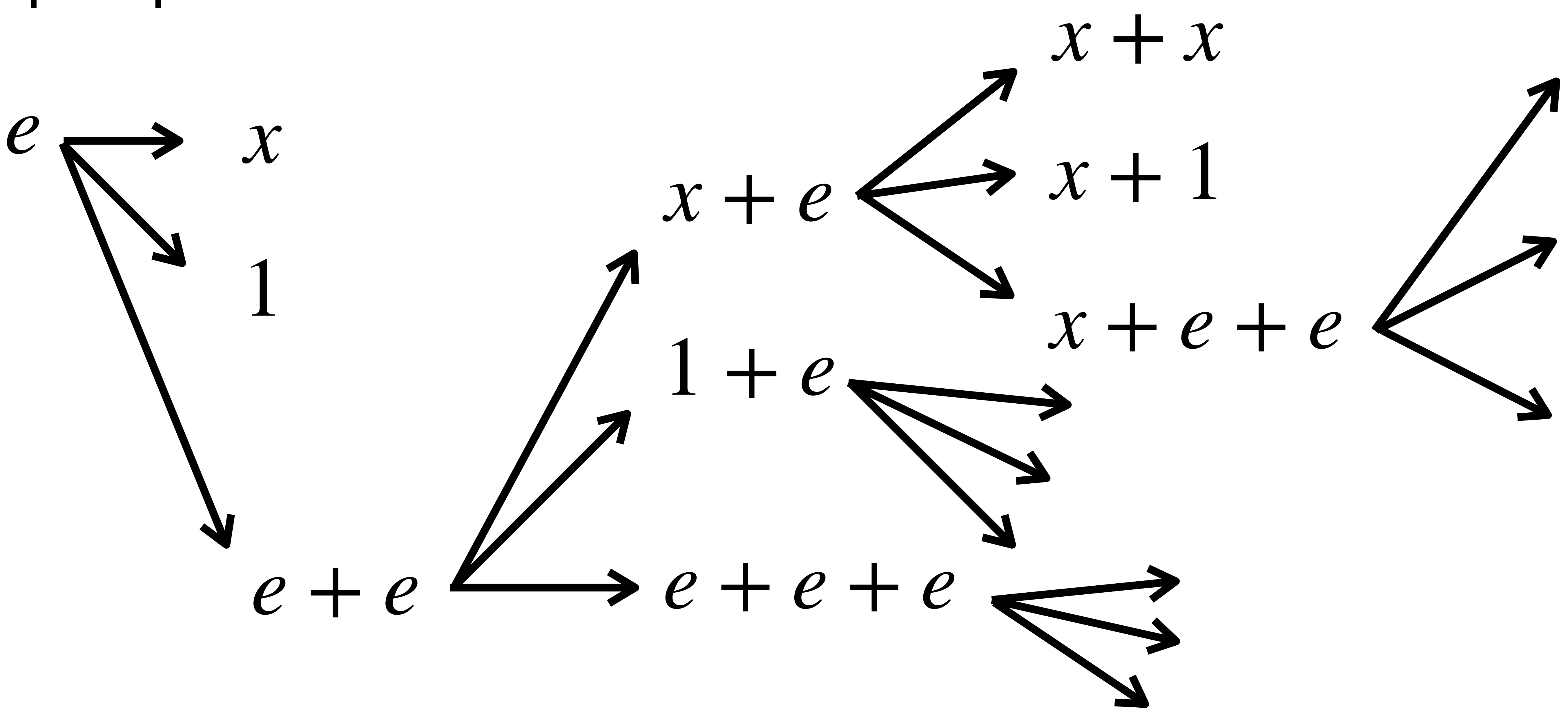
- Search-based
- Representation-based
- Using constraint solving
- Stochastic
- Neural approaches
- …

PBE technique 1: search-based

- Idea: enumerate programs from grammar **systematically** and test them on examples
- Observation 1: exhaustive, exponential
- Observation 2: random enumeration order may not work well
- Challenges — scalability & ambiguity
  - Today's lecture: two systematic search-based approaches (top-down & bottom-up)
  - Subsequent paper presentations: scale, resolve ambiguity

Top-down search

- We have already seen how this works
  - CFG: $e := x \mid 1 \mid e + e$



- Idea: start from start symbol, expand non-terminal symbols according to production rules, until reaching a program that satisfies examples

Top-down search (cont'd)

- Algorithm skeleton

```
top-down-search( (T, N, P, S), E ):
  worklist := { S };
  while ( worklist is not empty ):
    pp := worklist.remove();
    if ( pp is complete & pp satisfies E ): return pp;
    worklist.addAll( expand(pp) );
```

T: terminal symbols

N: non-terminal symbols

P: productions

S: start symbol

expand(pp): return more partial programs by replacing a non-terminal in pp

An example

```
top-down-search( (T, N, P, S), E ):
  worklist := { S };
  while ( worklist is not empty ):
    pp := worklist.remove();
    if ( pp is complete & pp satisfies E ): return pp;
    worklist.addAll( expand(pp) );
```

- CFG: $e := x \mid 1 \mid e + e$
- Example: $(1,2)$
- Worklist (at end of iterations)

iter 0: e

iter 1: x 1 $e + e$

iter 2: 1 $e + e$

iter 3: $e + e$

iter 4: $x + e$ $1 + e$ $e + e + e$
$e + x$ $e + 1$ $e + e + e$

iter 5: $x + x$ $x + 1$ $x + e + e$
$1 + e$ $e + e + e$
$e + x$ $e + 1$ $e + e + e$

iter 6: **return** $x + x$

Bottom-up search

- Idea: start with terminal symbols, combine smaller programs into bigger programs according to production rules, until reaching a program that satisfies examples

- Algorithm skeleton

bottom-up-search($(T, N, P, S), E$):

  worklist := { t | t $\in T$ };

  while (true):

    foreach p **in** worklist: **if** (p *is complete* & p *satisfies* E): **return** p;

    worklist.addAll(grow(worklist));

return more programs by applying production rules to programs in worklist

An example

```
bottom-up-search( (T, N, P, S), E ):
  worklist := { t | t ∈ T };
  while ( true ):
    foreach p in worklist: if ( p is complete & p satisfies E ): return p;
    worklist.addAll( grow(worklist) );
```

- CFG: $e := x \mid 1 \mid e + e$
- Example: $(1,2)$
- Worklist (at end of iterations)

iter 0: x 1

iter 1: x 1 $x + x$ $x + 1$ $1 + x$ $1 + 1$

iter 2: **return** $x + x$

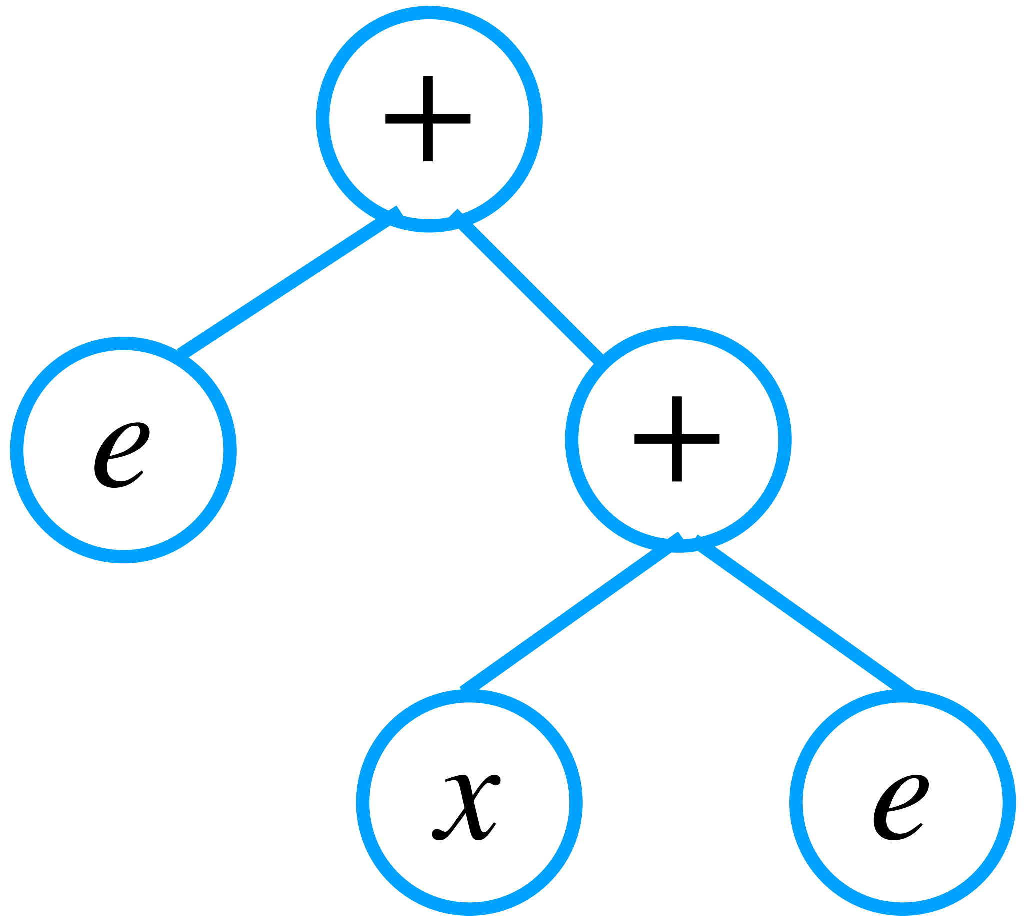
Top-down vs. bottom-up

Top-down

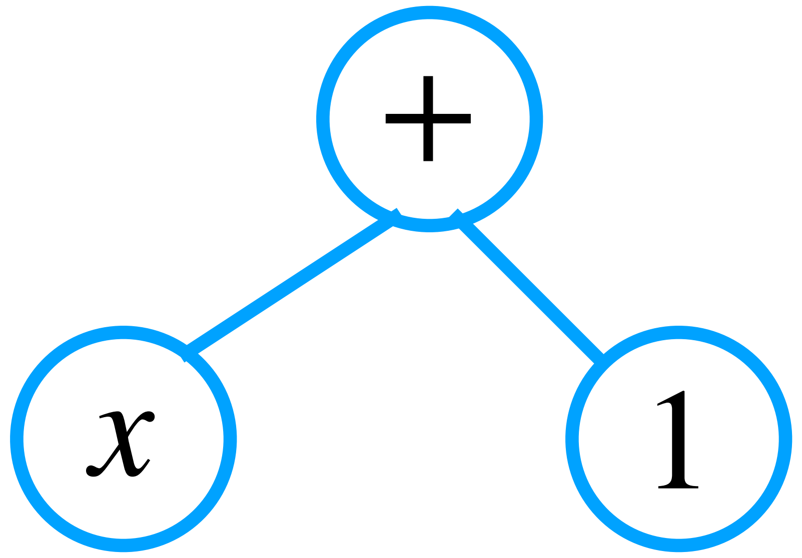
Bottom-up

Both exhaustive and brute-force procedures
(both can be implemented using worklist algorithm)

- Generate programs top-down
- Candidates in worklist are partial programs



- Generate programs bottom-up
- Candidates are concrete programs



Search-based approaches: scalability & ambiguity

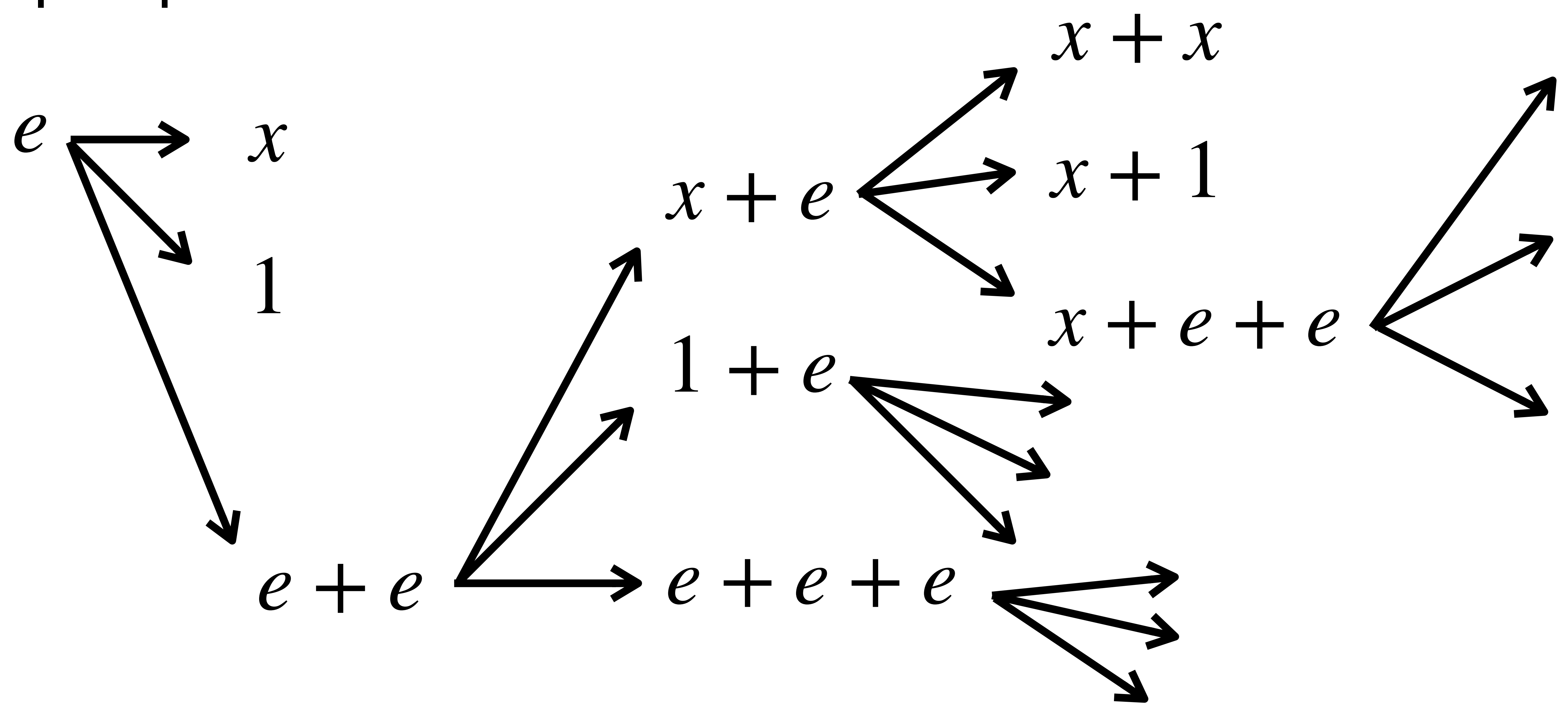
- Scalability — how to make search faster?
  - Pruning
    - Top-down: eliminate "incorrect" partial programs
    - Bottom-up: discard "unpromising" sub-programs
  - Prioritization
    - Better order of candidates in worklist

- Ambiguity — how to find intended program (not arbitrary one satisfying examples)?
  - Ranking (similar idea to prioritization)

- Will talk more in paper presentations

PBE technique 2: representation-based

- Idea: represent search space **explicitly**, then use representation to better guide search
  - CFG: $e := x \mid 1 \mid e + e$



- Challenge: how to construct representation efficiently, how to use it for synthesis

Different representations

- Version space algebras (VSAs) [Gulwani et al. 11]
- Finite tree automata (FTAs) [Wang et al. 17]
- Petri nets [Feng et al. 17]
- Type-transitions nets [Guo et al. 20]

Version space algebra

- Idea: construct a compact data structure (i.e., an VSA) that succinctly represents all programs consistent with examples

- Construction is top-down
  - FlashFill paper [Gulwani 11] has more details (will discuss in presentation)
  - [Polozov et al. 15] — VSA-based program synthesis framework

Finite tree automaton

- Idea: construct a compact data structure (i.e., an FTA) that succinctly represents all programs consistent with examples
  - Same idea as VSA, but different data structure
- Construction is bottom-up
  - Dace paper [Wang et al. 17] has more details (will discuss in presentation)
  - [Wang et al. 18] — FTA-based program synthesis framework

Summary of this lecture

- Syntax-guided synthesis (SyGuS): both semantic and syntactic constraints
- Programming-by-example (PBE): examples as spec
- Two PBE techniques: search-based & representation-based