# #18: Program Sketching and CEGIS

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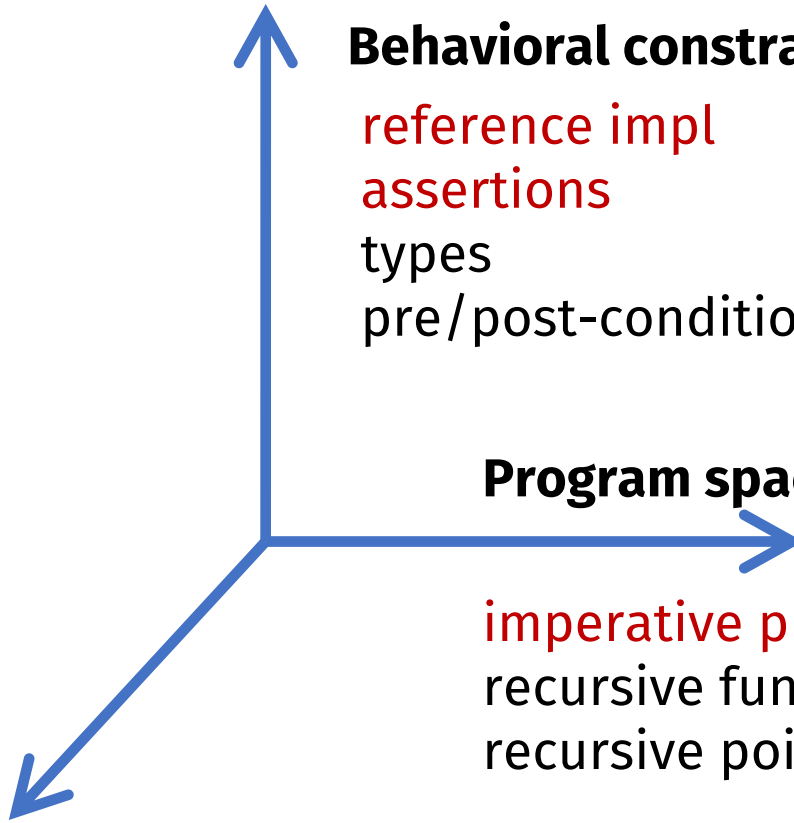
EECS 700: Introduction to Program Synthesis

# Program Sketching



**Behavioral constraints**

reference impl
assertions
types
pre/post-conditions

+ bounded guarantees

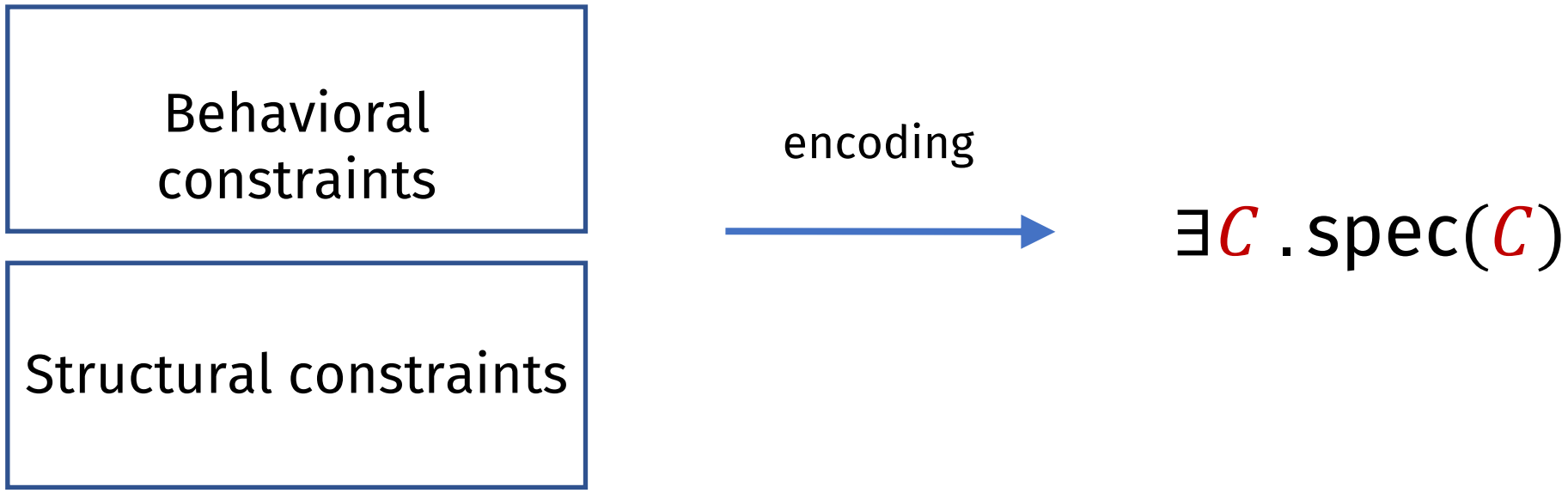
**Program space**

imperative programs w/ loops
recursive functional programs
recursive pointer-manipulating programs

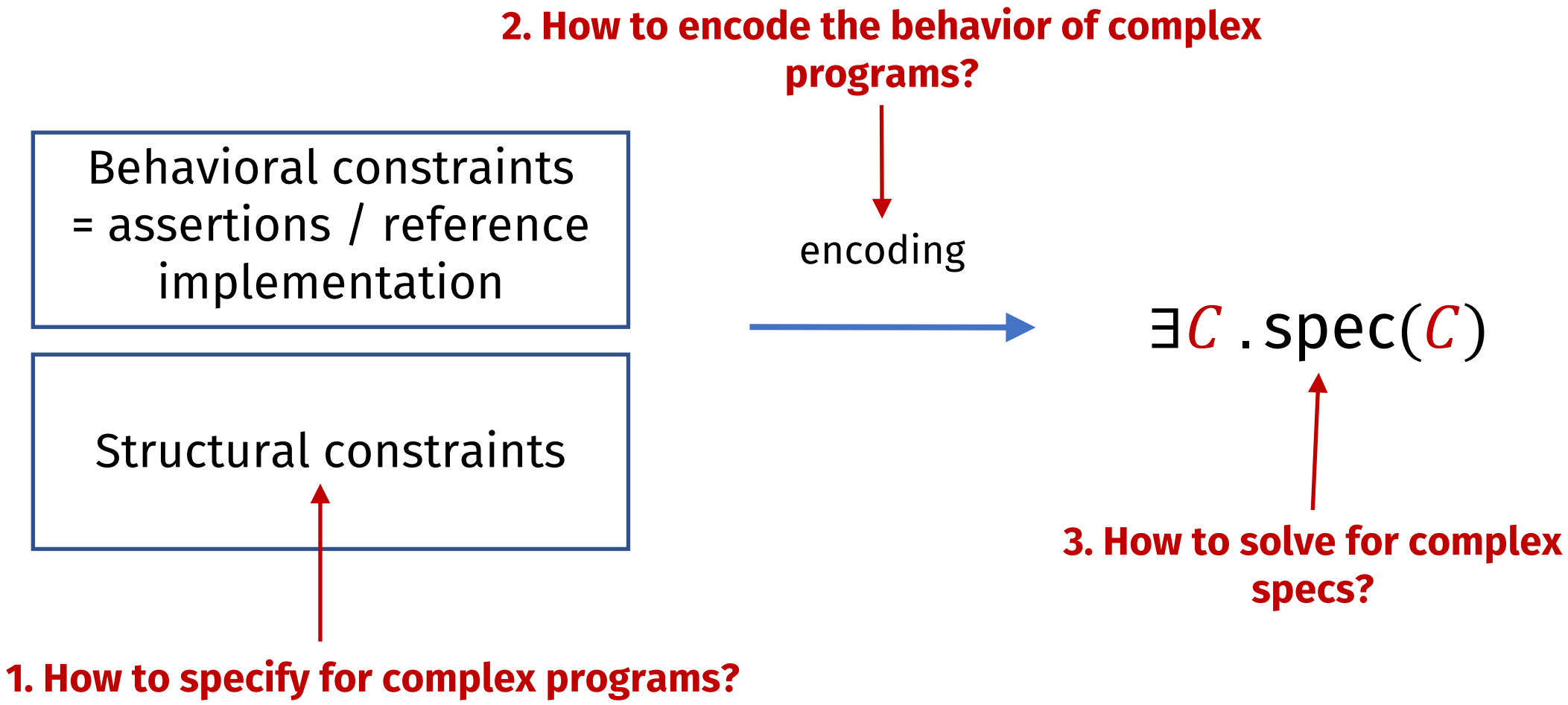
**Search strategy**

enumerative
constraint-based
deductive

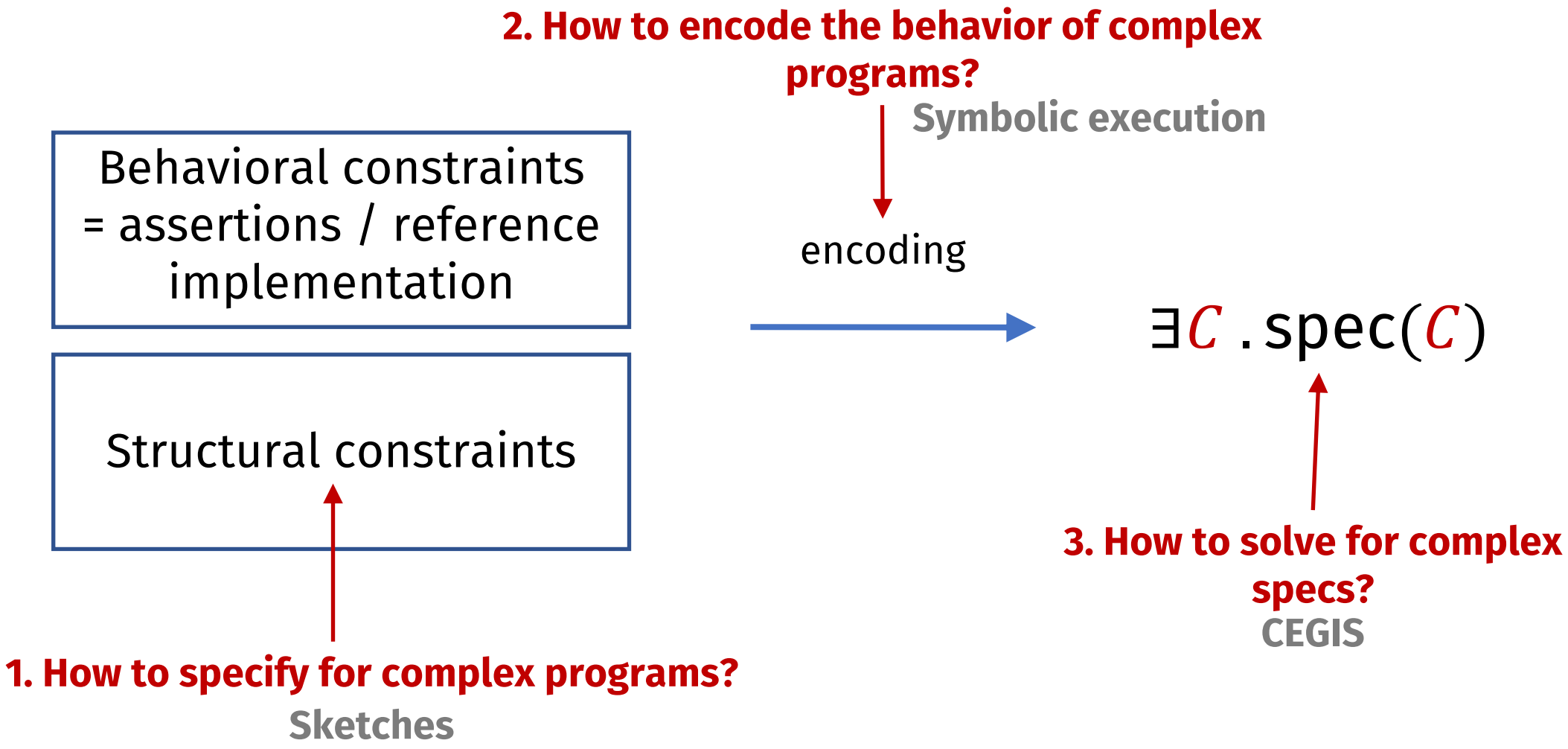
# Constraint-based synthesis



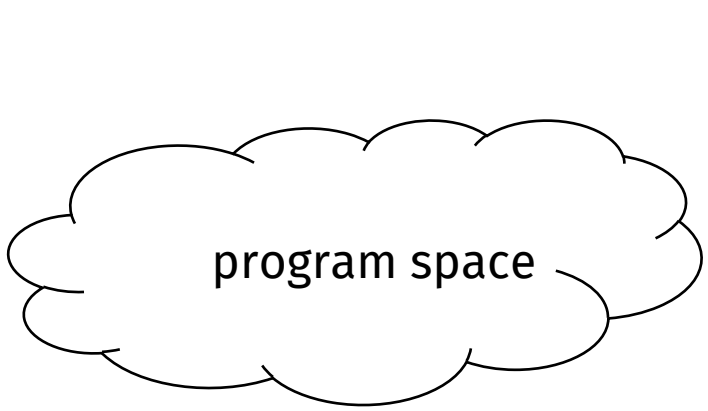
# CBS for complex programs



# Program Sketching



# CBS from examples




E = [i → o]

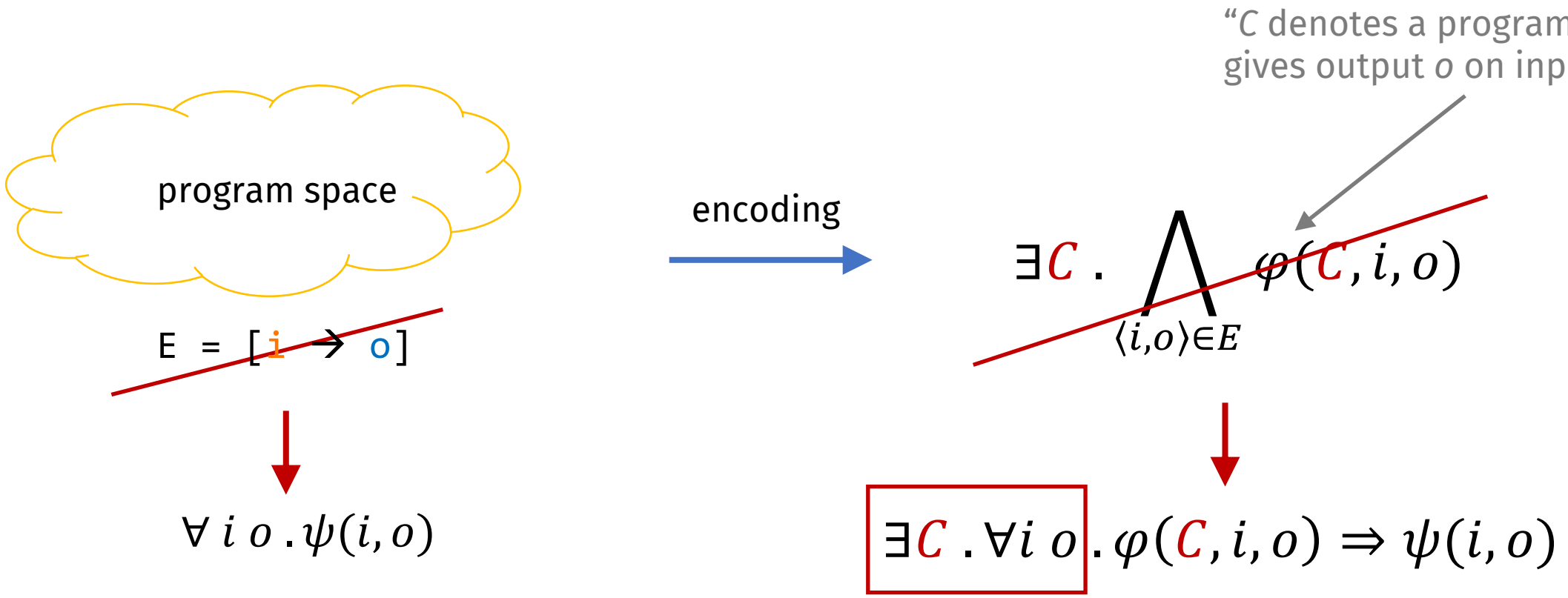
encoding

Parameters (control vector)

"$C$ denotes a program that gives output $o$ on input $i$"

$$\exists C \,.\, \bigwedge_{\langle i,o\rangle \in E} \varphi(C, i, o)$$

# CBS from specifications



# Example

```
harness void main(int x) {
  int y := ?? * x + ??;
  assert y - 1 == x + x;
}
```

encoding

$$\exists C \,.\, \forall i\ o \,.\, \varphi(C, i, o) \Rightarrow \psi(i, o)$$

$$\exists c_1 c_2 \,.\, \forall x\ y \,.\, y = c_1 * x + c_2 \Rightarrow y - 1 = x + x$$

simplify

$$\exists c_1 c_2 \,.\, \forall x \,.\, c_1 * x + c_2 - 1 = x + x$$

How do we solve this constraint?

# CEGIS

$$\exists c \,.\, \forall x \,.\, Q(c, x)$$

- **Idea 1:** Bounded Observation Hypothesis
  - Assume there exists a small set of inputs $\mathrm{X} = \{x_1, x_2, \ldots x_n\}$ such that whenever $c$ satisfies

$$\bigwedge_{i \in 1..n} Q(c, x_i)$$

No quantifiers here, can give to SAT / SMT

  it also satisfies

$$\forall x. Q(c, x)$$

# Example

This is a linear constraint, two inputs are enough!

$$\exists c_1 c_2 \,.\, \forall x \,.\, c_1 * x + c_2 - 1 = x + x$$

$$X = \{0, 1\}$$

$$Q(c_1, c_2, 0) \equiv c_2 - 1 = 0$$

$$Q(c_1, c_2, 1) \equiv c_1 + c_2 - 1 = 2$$

$$\{c_1 \to 2, c_2 \to 1\}$$

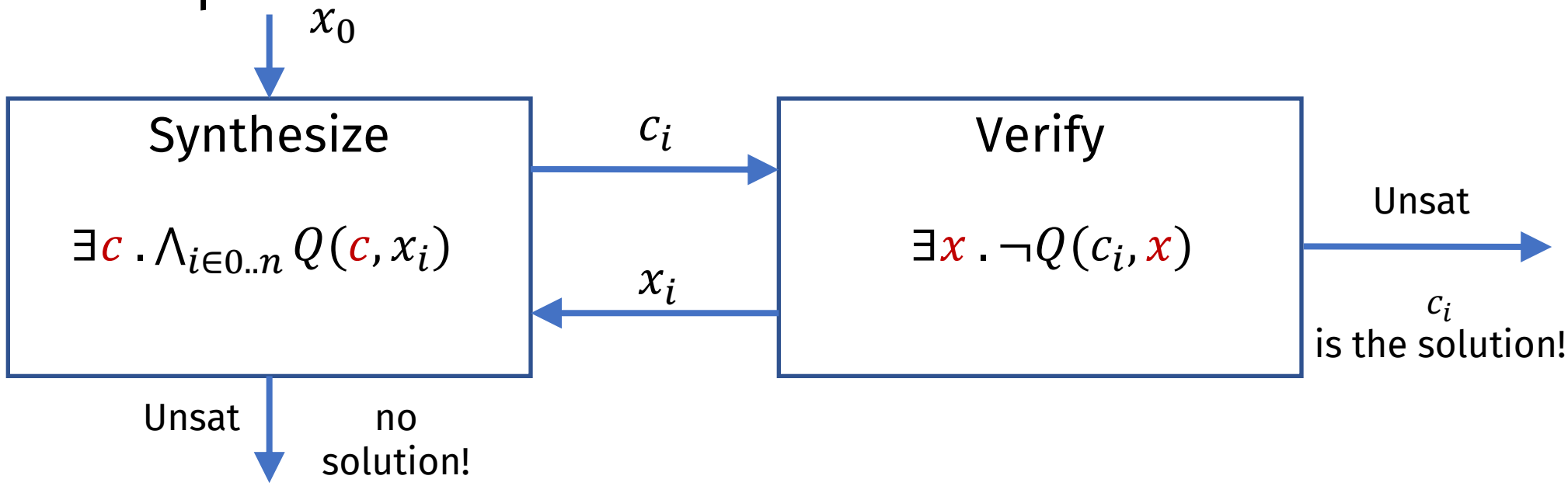
```
harness void main(int x) {
  int y := 2 * x + 1;
  assert y - 1 == x + x;
}
```

How do we find X in a general case?

# CEGIS

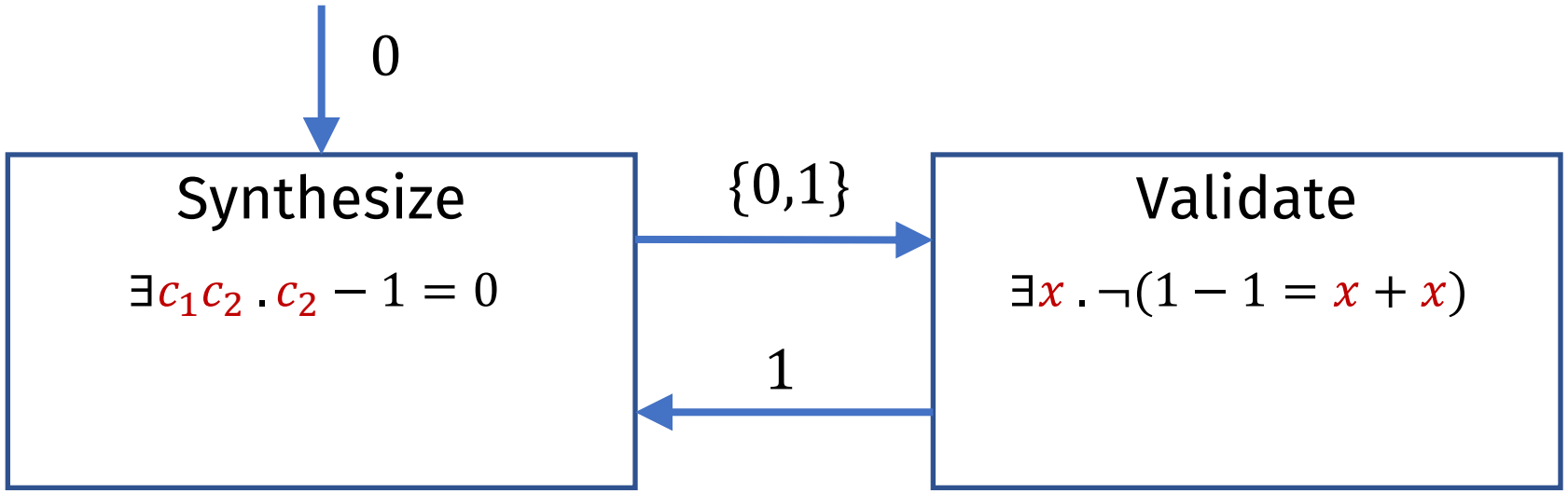
$$\exists c \,.\, \forall x \,.\, Q(c, x)$$

- **Idea 2:** Rely on verification oracle to generate counterexamples



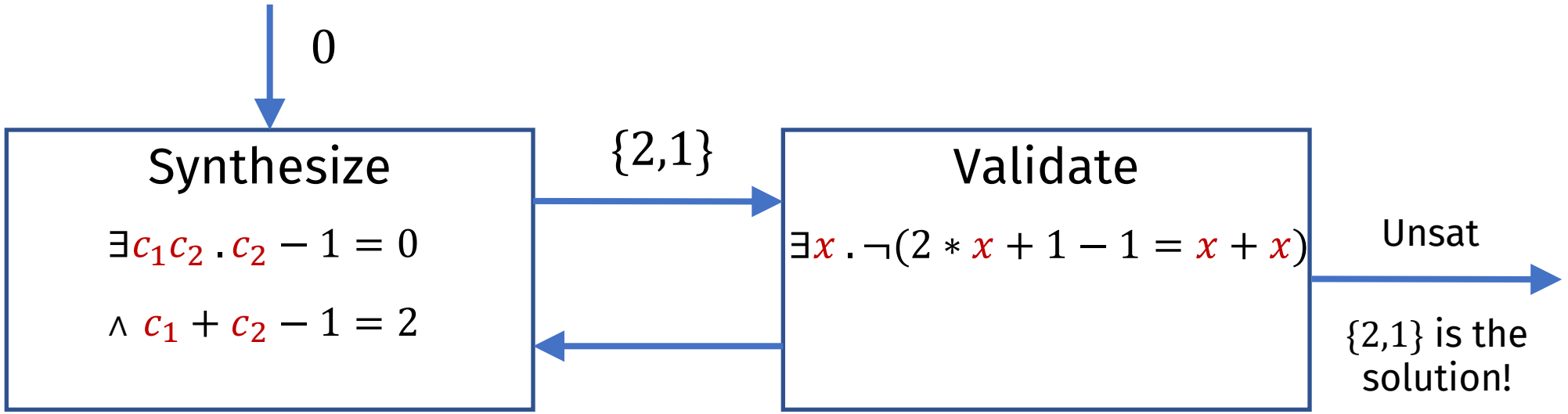
# Example

$$\exists c_1 c_2 \,.\, \forall x \,.\, c_1 * x + c_2 - 1 = x + x$$



# Example

$$\exists c_1 c_2 \,.\, \forall x \,.\, c_1 * x + c_2 - 1 = x + x$$



# Program Sketching

**2. How to encode the behavior of complex programs?**

Symbolic execution

Behavioral constraints = assertions / reference implementation

Structural constraints

encoding

$$\exists C \,.\, \forall x \,.\, Q(C, x)$$

**3. How to solve for complex specs?**

CEGIS

**1. How to specify for complex programs?**

Sketches

# Structural constraints in Sketch

- Different constraints good for different problems
  - CFGs
  - Components
  - Just figure out the constants
- **Idea:** Allow the programmer to encode all kinds of constraints using… programs (duh!)

# Language Design Strategy

Extend base language with one construct

Constant hole: **??**

```
int bar (int x)
{
    int t = x * ??;
    assert t == x + x;
    return t;
}
```

```
int bar (int x)
{
    int t = x * 2;
    assert t == x + x;
    return t;
}
```

Synthesizer replaces **??** with a natural number

# Constant holes → sets of expressions

- Expressions with `??` == sets of expressions
  - linear expressions `x * ?? + y * ??`
  - polynomials `x * x * ?? + x * ?? + ??`
  - sets of variables `?? ? x : y`

# Example: swap without a temporary

- Swap two integers without an extra temporary

```
void swap(ref int x, ref int y){
    x = ... // sum or difference of x and y
    y = ... // sum or difference of x and y
    x = ... // sum or difference of x and y
}

harness void main(int x, int y){
    int tx = x; int ty = y;
    swap(x, y);
    assert x==ty && y == tx;
}
```

# Syntactic sugar

- {| RegExp |}

- RegExp supports choice '|' and optional '?'
  - can be used arbitrarily within an expression
    - to select operands `{| (x | y | z) + 1 |}`
    - to select operators `{| x (+ | -) y |}`
    - to select fields `{| n(.prev | .next)? |}`
    - to select arguments `{| foo( x | y, z) |}`

- Set must respect the type system
  - all expressions in the set must type-check
  - all must be of the same type

# Complex program spaces

- **Idea:** To build complex program spaces from simple program spaces, borrow abstraction devices from programming languages
- Function: abstracts expressions
- Generator: abstracts set of expressions
  - Like a function with holes…
  - …but different invocations → different code

# Example: swap without a temporary

```
generator int sign() {
    if ?? {return 1;} else {return -1;}
}

void swap(ref int x, ref int y){
    x = x + sign()*y;          ➔  1
    y = x + sign()*y;          ➔ -1
    x = x + sign()*y;          ➔ -1
}

harness void main(int x, int y){
    int tx = x; int ty = y;
    swap(x, y);
    assert x==ty && y == tx;
}
```

# Recursive generators

- Can generators encode a CFG?

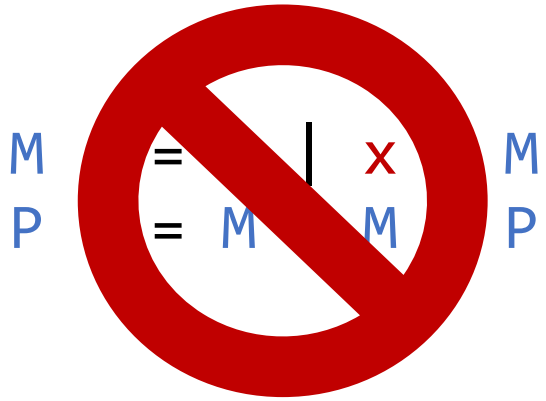
```
M ::= n | x * M
P ::= M | M + P
```

```
generator int mono(int x) {
    if (??) {return ??;}
    else {return x * mono(x);}
}

generator int poly(int x) {
    if (??) {return mono(x);}
    else {return mono(x) + poly(x);}
}
```

# Recursive generators

- What if monomial of every degree can occur at most once?




```
generator int mono(int x, int n) {
    if (n <= 0) {return ??;}
    else {return x * mono(x, n - 1);}
}

generator int poly(int x, int n) {
    if (n <= 0) {return mono(x,0);}
    else {return mono(x,n) + poly(x, n - 1);}
}
```

# Program Sketching