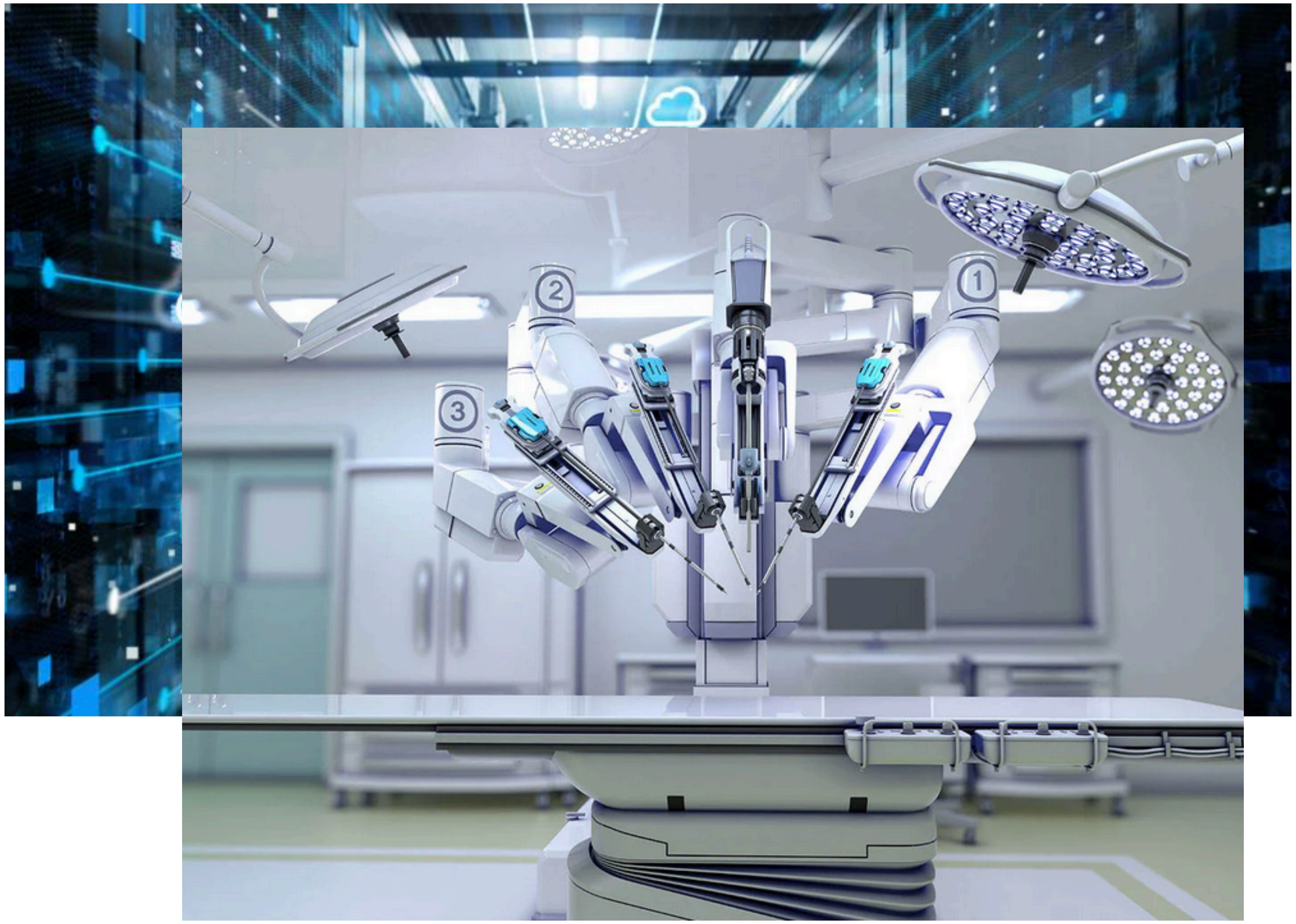
Correctness and Verification using Software Contracts

Thomas Gilray

Associate Professor
Washington State University
https://thomas.gilray.org/

WASHINGTON STATE
UNIVERSITY


2
1
3

787
ANA

“riddled with bugs”

“spaghetti-like”

http://www.safetyresearch.net/blog/articles/toyota-unintended-acceleration-and-big-bowl-%E2%80%9Cspaghetti%E2%80%9D-code

What to do about “worse is better”?

Richard P. Gabriel. “The rise of worse is better.”

Firm/discrete concerns

- Correctness properties
- Security/Robustness
- Can the program “go wrong”—exhibit a class of bugs, vulnerabilities

Soft/continuous concerns

- Simplicity/Maintainability
- Time to market
- Performance/Optimization
- Feature set/Completeness

“Worse is better”

Soft/continuous concerns

- Correctness properties
- Security/Robustness
- Can the program “go wrong”—exhibit a class of bugs, vulnerabilities

Firm/discrete concerns

- Simplicity/Maintainability
- Time to market
- Performance/Optimization
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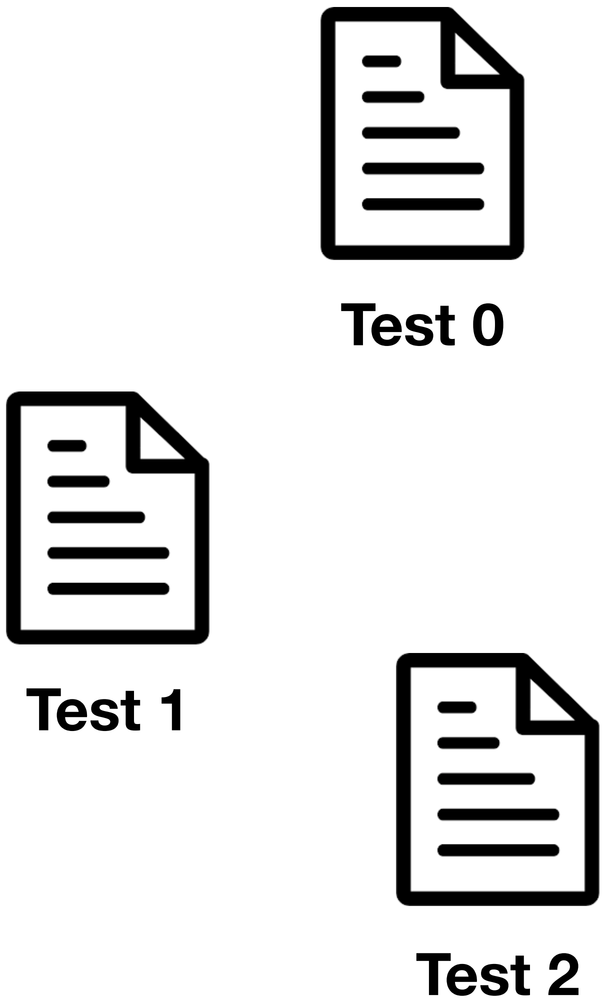
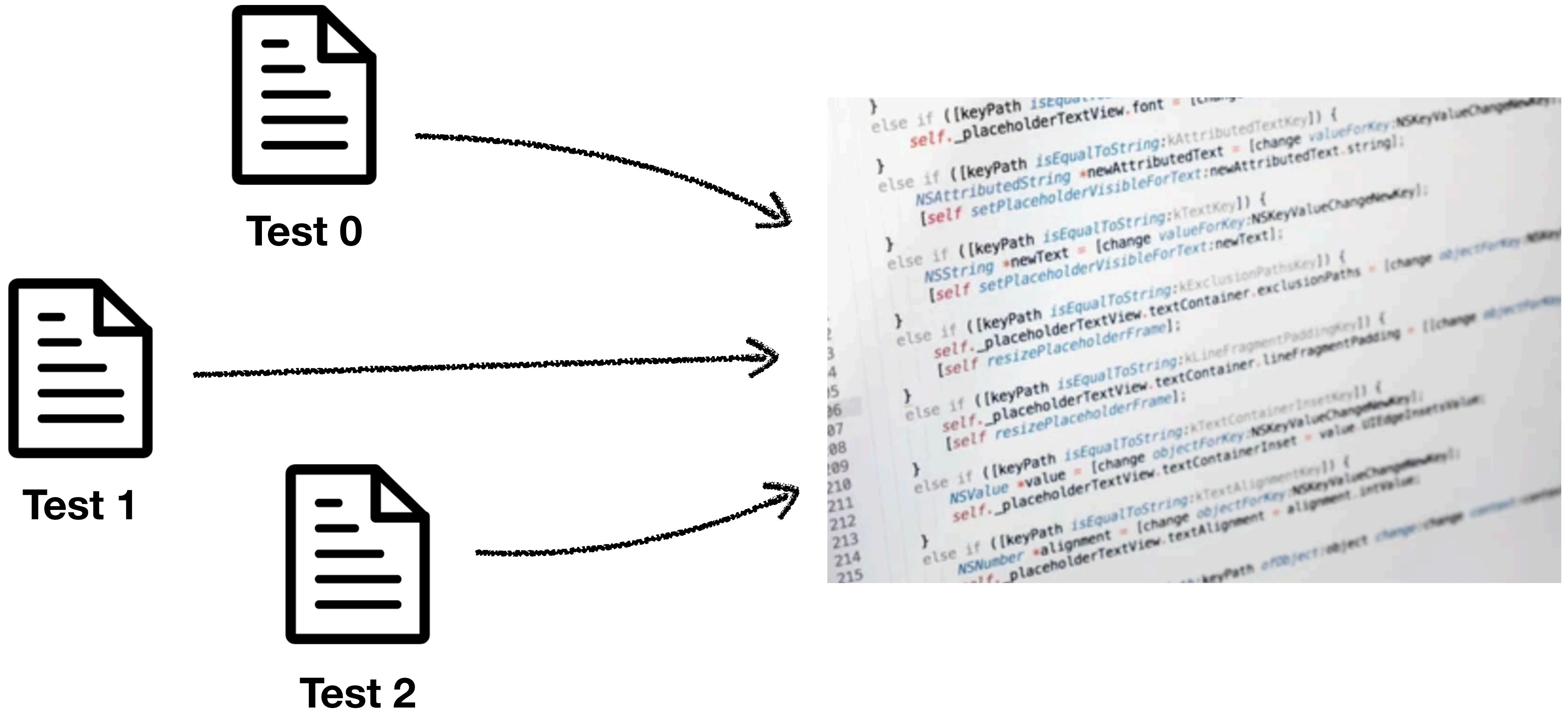
Test-driven Development

Test-driven Development

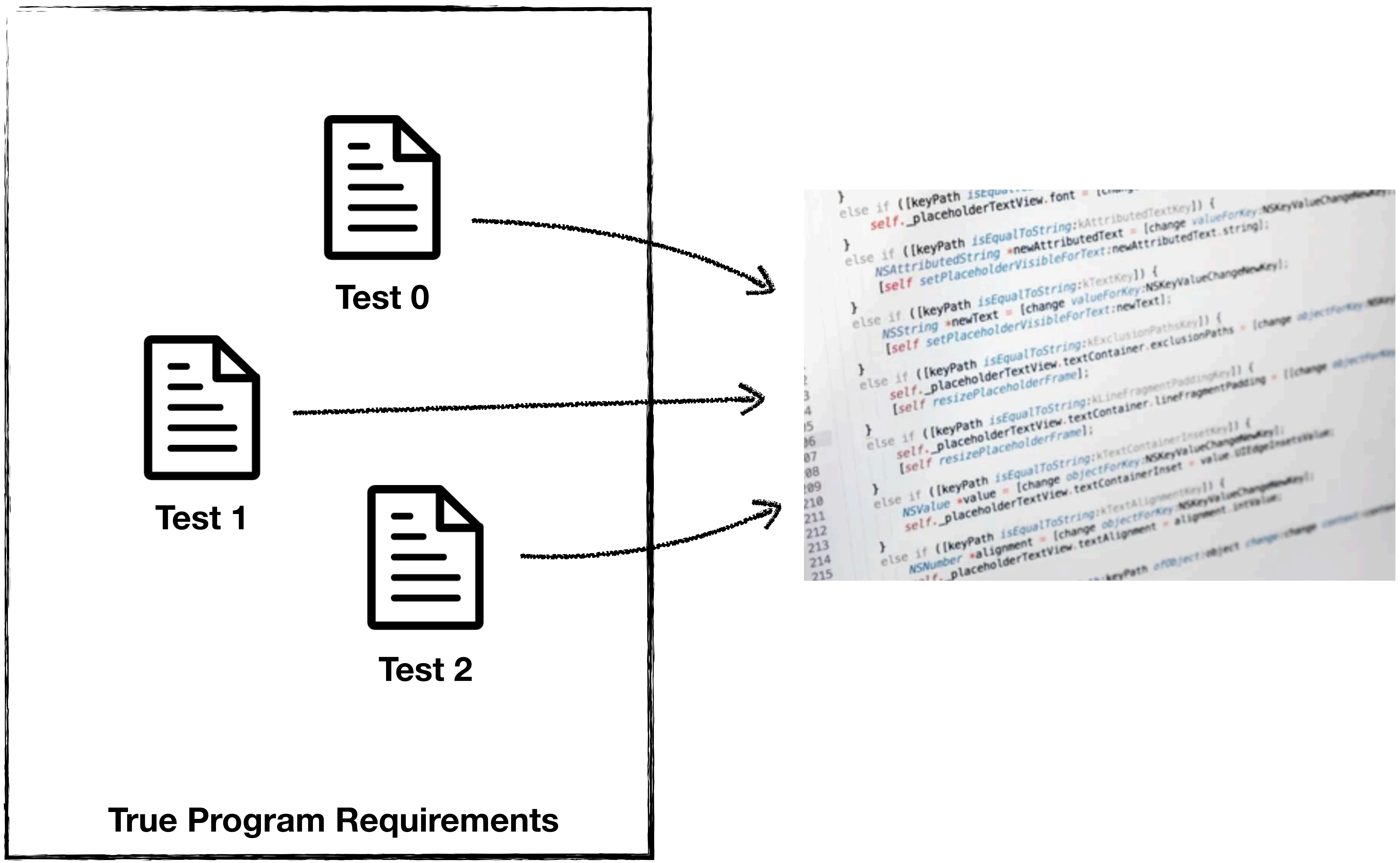


Test-driven Development

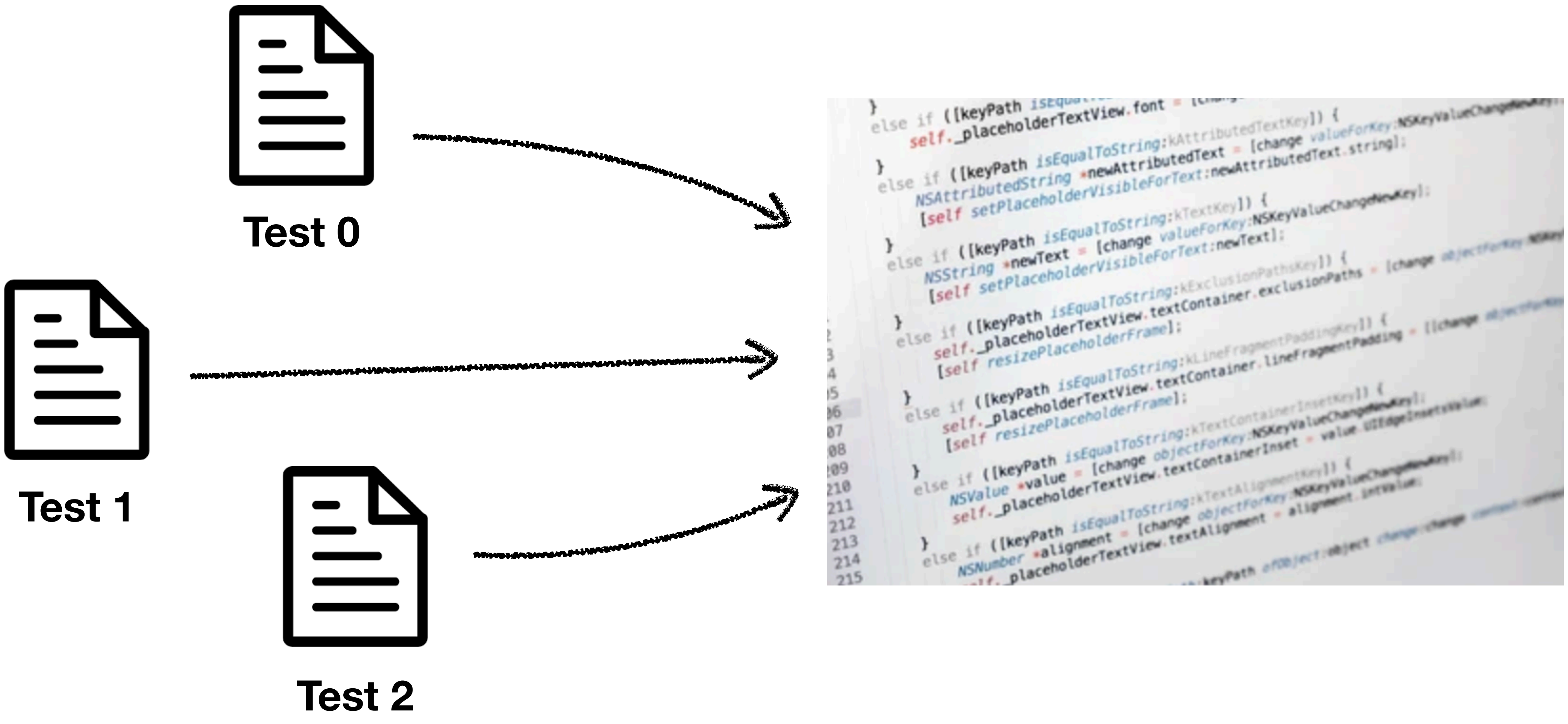


```
}
else if ([keyPath isEqual
    self._placeholderTextView.font = [chang
}
else if ([keyPath isEqualToString:kAttributedTextKey]) {
    NSAttributedString *newAttributedText = [change valueForKey:NSKeyValueChangeNewKey];
    [self setPlaceholderVisibleForText:newAttributedText.string];
}
else if ([keyPath isEqualToString:kTextKey]) {
    NSString *newText = [change valueForKey:NSKeyValueChangeNewKey];
    [self setPlaceholderVisibleForText:newText];
}
else if ([keyPath isEqualToString:kExclusionPathsKey]) {
    self._placeholderTextView.textContainer.exclusionPaths = [change objectForKey:NSKey
    [self resizePlaceholderFrame];
}
else if ([keyPath isEqualToString:kLineFragmentPaddingKey]) {
    self._placeholderTextView.textContainer.lineFragmentPadding = [[change objectForKe
    [self resizePlaceholderFrame];
}
else if ([keyPath isEqualToString:kTextContainerInsetKey]) {
    NSValue *value = [change objectForKey:NSKeyValueChangeNewKey];
    self._placeholderTextView.textContainerInset = value.UIEdgeInsetsValue;
}
else if ([keyPath isEqualToString:kTextAlignmentKey]) {
    NSNumber *alignment = [change objectForKey:NSKeyValueChangeNewKey];
    self._placeholderTextView.textAlignment = alignment.intValue;
}
                                 keyPath ofObject:object change:change cont
```

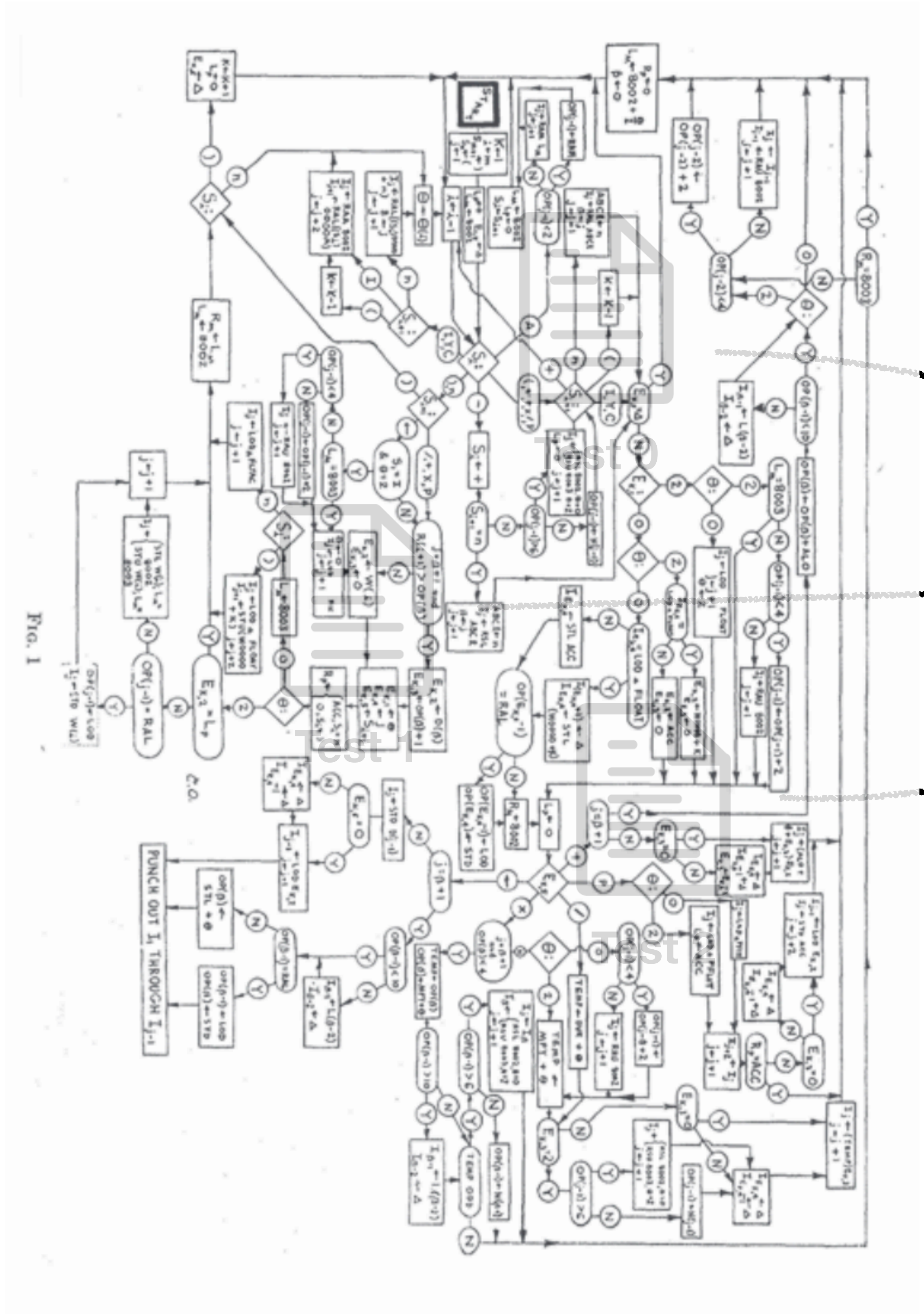
Test-driven Development



Specification-driven Development



Specification-driven Development



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Contract-driven Development

"*design by contract*"

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```

Contract-driven Development

"design by contract"

So, what is a ***contract*** anyway?

contract noun

con·tract | \ˈkän-ˌtrakt \

Definition of *contract* (Entry 1 of 3)

1 a **:** a binding agreement between two or more persons or parties *especially* **:** one legally enforceable

// If he breaks the *contract*, he'll be sued.

contract *noun*

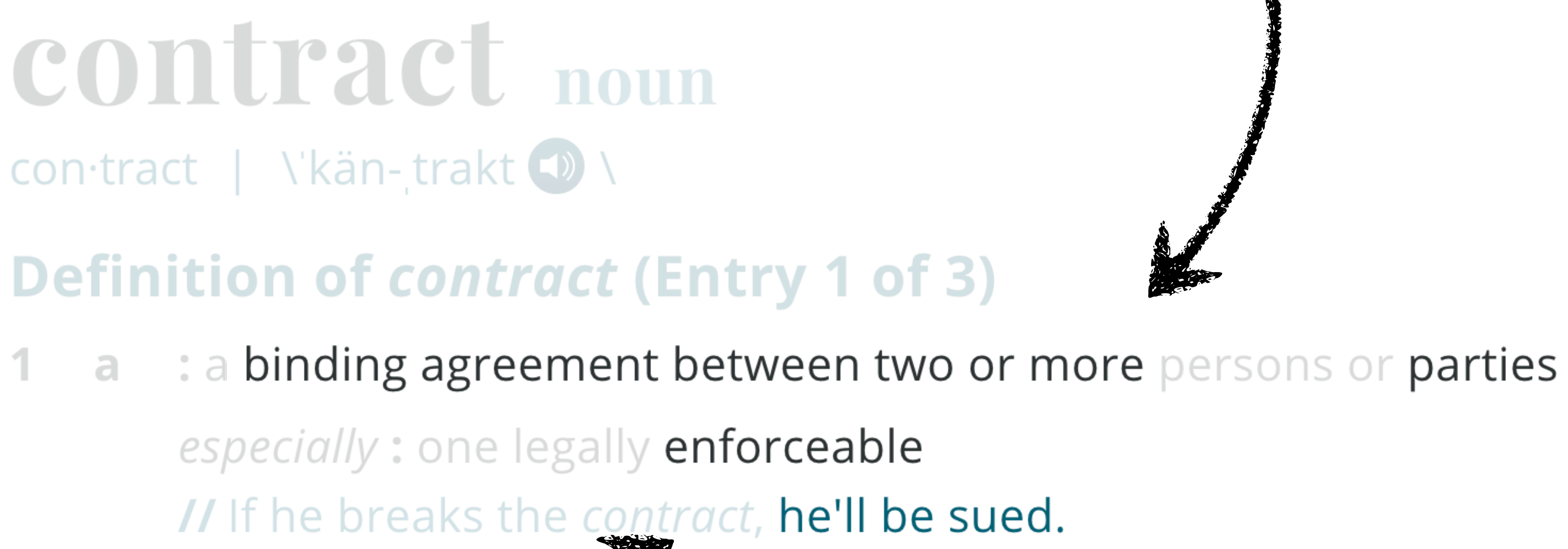
con·tract | \ˈkän-ˌtrakt \

Definition of *contract* (Entry 1 of 3)

1 **a** **:** a binding agreement between two or more persons or parties *especially* **:** one legally enforceable

// If he breaks the *contract*, he'll be sued.

An agreement between multiple parties for mutual benefit.



contract noun

con·tract | \ˈkän-ˌtrakt \

Definition of *contract* (Entry 1 of 3)

1 a : a binding agreement between two or more persons or parties

especially : one legally enforceable

// If he breaks the *contract*, he'll be sued.

The agreement is enforced and violations are blamed on an offending party.

```
    }

    return e;
}
```

A reallocating array<T> class in C++

```
void insert(const T& ele, u64 index = 0)
{
    assert(length >= index);

    if (length+1 > buff_length)
    {
        // reallocate buffer
        T* oldbuff = buff;

        buff_length *= 2;
        buff = allocator.alloc(buff_length);

        // copy old data
        for (u64 i = 0; i < length; ++i)
        {
    }

    return e;
}


void insert(const T& ele, u64 index = 0)
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        buff_length *= 2;
        buff = allocator.alloc(buff_length);

        // copy old data
        for (u64 i = 0; i < length; ++i)
    }

    return e;
}


void insert(const T& ele, u64 index = 0)
{
    // Precondition:
    assert(length >= index);
    assert(length <= buff_length);

    // ... insert, possible reallocation ...
```

```
    // Postcondition:
    assert(length <= buff_length);
}
```

A reallocating array<T> class in C++

A reallocating array<T> class in C++

```
    }

    return e;
}


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{
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    assert(length >= index);
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    // ... insert, possible reallocation ...



    // Postcondition:
    assert(length <= buff_length);
}
```

Meyer’s “Design by Contract”

Implemented in Meyer’s **Eiffel** programming language,
a typed, object-oriented language with contracts at the center.

“A contract carries mutual **obligations** and **benefits**.”

“Design by contract”. **Bertrand Meyer. 1986.**

Applying “Design by Contract”

```
put_child (new: NODE) is
  require
    new /= Void
  do

    -- Insertion algorithm

  ensure
    new.parent = Current
    child_count = old child_count + 1
  end
```

“Applying design by contract”. **Bertrand Meyer. 1992.**

Applying “Design by Contract”

Precondition

Postcondition

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put_child (new: NODE) is
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  ensure
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  end
```

“Applying design by contract”. **Bertrand Meyer. 1992.**

Preconditions

To call `put_child`, calling code must satisfy its **obligations**

`put_child(n)`

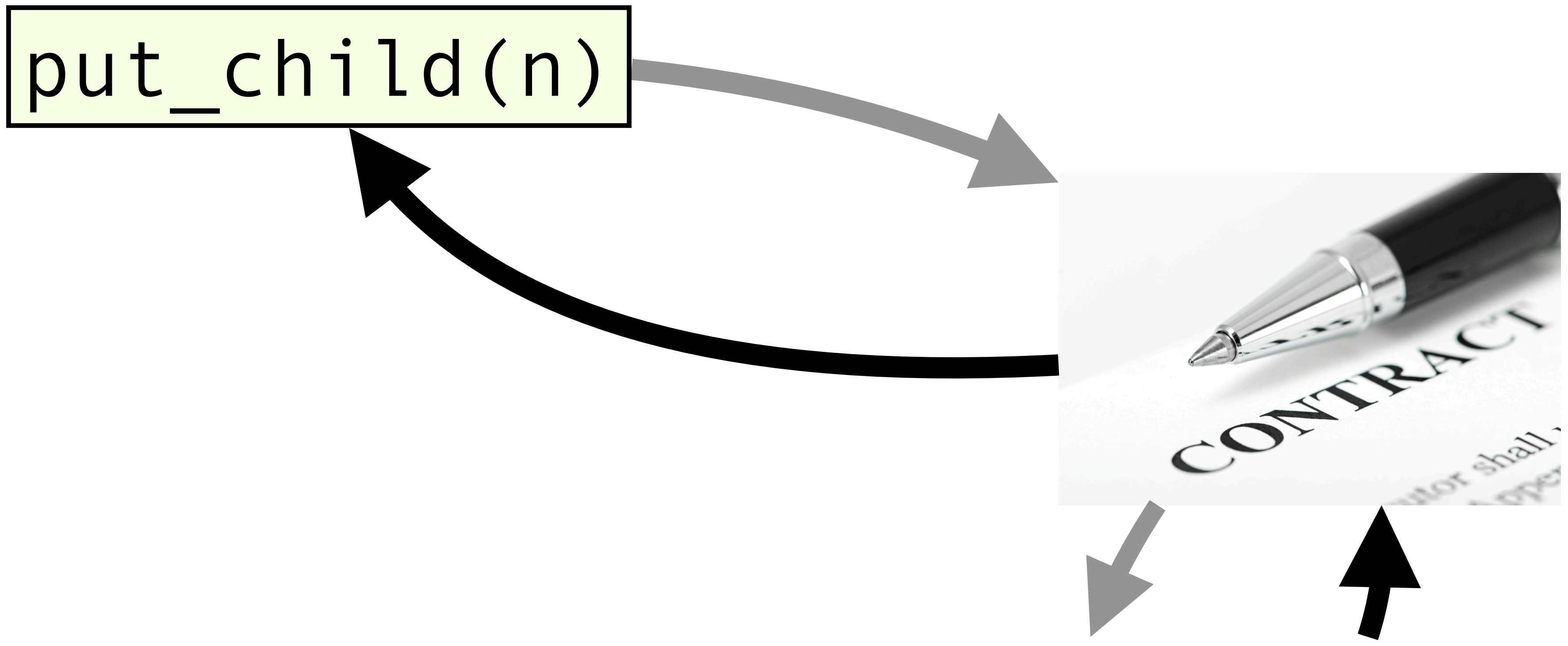
```
put_child (new: NODE) is
  require
    new /= Void
  do

    -- Insertion algorithm

  ensure
    new.parent = Current
    child_count = old child_count + 1
  end
```

Postconditions

To return `put_child`, must ensure it provides **benefits**



```
put_child (new: NODE) is
  require
    new /= Void
  do

    -- Insertion algorithm

  ensure
    new.parent = Current
    child_count = old child_count + 1
  end
```

If client **breaks** contract, `put_child` is not obligated to provide benefits

```
put_child(Void)
```

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put_child (new: NODE) is
  require
    new /= Void
  do

    -- Insertion algorithm

  ensure
    new.parent = Current
    child_count = old child_count + 1
  end
```

If client **breaks** contract,

`put_child` is not obligated to provide benefits

`put_child(Void)`

`not (Void /= Void)` 😥

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`put_child(Void)`

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    new.parent = Current
    child_count = old child_count + 1
  end
```

If client **breaks** contract,
`put_child` is not obligated to provide benefits

```
put_child(                                        Void) 😥
```

```
ensure
   new.parent = Current
   child_count = old child_count + 1
end
```

Contracts are a ***linguistic mechanism***

implemented as a *built-in feature* of the language, using *source-to-source translation*, or *using a macro system*.

```
/**
 *  @pre n >= 0
 *  @post return >= 1
 */
public static int fact(int n) {
    if (n <= 1) return 1;
    else return n * fact(n-1);
}
```

factorial in Java (e.g., using jContract)

```
/**
 *  @pre n >= 0
 *  @post return >= 1
 */
public static int fact(int n) {
    if (n <= 1) return 1;
    else return n * fact(n-1);
}
```

factorial in Java (e.g., using jContract)

```
public static int fact(int n) {
    assert n >= 0;
    if (n <= 1) {
        assert 1 >= 1;
        return 1;
    } else {
        int rv = n * fact(n-1);
        assert rv >= 1;
        return rv;
    }
}
```

factorial in Java (e.g., using jContract)

```
public static int fact(int n) {
    assert n >= 0;
    if (n <= 1) {
        assert 1 >= 1;
        return 1;
    } else {
        int rv = n * fact(n-1);
        assert rv >= 1;
        return rv;
    }
}
```

The contract bakes dynamic checks into the source code, executed at every evaluation of fact(n)!

“Contracts for higher-order functions”. **Findler, Felleisen. 2002.**

Contracts.js

“Hygienic Macros for JavaScript”. **Tim Disney. 2015**

Contracts.js

Try it out online!

http://www.contractsjs.org/#/examples

“Hygienic Macros for JavaScript”. **Tim Disney. 2015**

```
// [number] -> [string]
function array_numtostr(arr) {
    assert(arr instanceof Array);

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(arr[i]+"");

    assert(str_arr instanceof Array);
    return str_arr
}
```

```
// [number] -> [string]
function array_numtostr(arr) {
    assert(arr instanceof Array);

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(arr[i]+"");

    assert(str_arr instanceof Array);
    return str_arr
}
```

```
// [number] -> [string]
function array_numtostr(arr) {
    assert(arr instanceof Array
        && arr.reduce((a,n)=>(typeof n)
=="number" && a, true));

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(arr[i]+"");

    assert(str_arr instanceof Array
        && str_arr.reduce((a,s)=>(typeof s)
=="string" && a, true));
    return str_arr
}
```

```
@ ([...Num]) -> [...Str]
function array_numtostr(arr) {

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(arr[i]+"");

    return str_arr
}
```

```
➡ @ ([...Num]) -> [...Str]
  function array_numtostr(arr) {

      var str_arr = [];
      for (var i = 0; i < arr.length; ++i)
          str_arr.push(arr[i]+"");

      return str_arr
  }
```

contracts.js's **@** macro allows the programmer to associate a function contract with `array_numtostr`

```
@ ([...Num], (Num)->Str) -> [...Str]
function array_numtostr(arr, format) {

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(format(arr[i]));

    return str_arr
}

array_numtostr([14,18],
    (n) => “0x"+n.toString(16))

// => ["0xe","0x12"]
```

```
@ ([...Num], (Num)->Str) -> [...Str]
function array_numtostr(arr, format) {

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(format(arr[i]));

    return str_arr
}

array_numtostr([14,18],
    (n) => “0x"+n.toString(16))

// => ["0xe","0x12"]
```

We can check that `arr` is an array, and that its elements are numbers…

```
@ ([...Num], (Num)->Str) -> [...Str]
function array_numtostr(arr, format) {
    assert(…??…);
    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(format(arr[i]));

    return str_arr;
}

array_numtostr([14,18],
    (n) => "0x"+n.toString(16))

//=> ["0xe","0x12"]
```

…but how can we check that `format` satisfies `(Num)->Str` *<u>before</u>* array_numtostr is evaluated?

`format` is a first-class function—a behavioral value!

Contracts on behavioral values are ***delayed.***

The contract `array_numtostr` requires on its argument `format` is enforced in the same way as the contract on `array_numtostr`!

"Contracts for higher-order functions". **Findler, Felleisen. 2002.**

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@ ([...Num], (Num)->Str) -> [...Str]
function array_numtostr(arr, format) {

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    return str_arr
}

array_numtostr([14,18], (n) => n)

// => ["0xe","0x12"]
```

```
Error: array_numtostr: contract violation
expected: Str
given: 14
in: the return of
    the 2nd argument of
    ([....Num], (Num) -> Str) -> [....Str]
function array_numtostr guarded at line: 4
blaming: (calling context for array_numtostr)
```

Higher-order contract systems track program labels alongside contracts to ***properly assign blame*** when failure occurs.

“Correct blame for contracts”. **Dimoulas. 2011.**

```
@ (a: [...Num], f: (Num)->Str)
    -> r: [...Str] | a.length == r.length
function array_numtostr(arr, format) {

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(format(arr[i]));

    return str_arr
}

array_numtostr([14,18],
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// => ["0xe","0x12"]
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Software contracts **Static typechecking**

"Refinement types for ML", **Freeman, Pfenning. 1991.**

Software contracts

- **Same expressivity** as the host programming language

Static typechecking

- **Separate type language** with a static semantics

"Refinement types for ML", **Freeman, Pfenning. 1991.**

Software contracts

- **Same expressivity** as the host programming language
- **Reports actual/observed errors** & witnesses to errors

Static typechecking

- **Separate type language** with a static semantics
- Reports **potential errors** in abstract terms

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Software contracts

- **Same expressivity** as the host programming language
- **Reports actual/observed errors** & witnesses to errors
- Can add **significant run-time overhead**, breaks tail calls

Static typechecking

- **Separate type language** with a static semantics
- Reports **potential errors** in abstract terms
- Produces fast code **without run-time monitoring** of types

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Software contracts

- **Same expressivity** as the host programming language
- **Reports actual/observed errors** & witnesses to errors
- Can add **significant run-time overhead**, breaks tail calls
- Error discovery is **delayed until runtime**

Static typechecking

- **Separate type language** with a static semantics
- Reports **potential errors** in abstract terms
- Produces fast code **without run-time monitoring** of types
- Potential failures are **discovered ahead of time**

"Refinement types for ML", **Freeman, Pfenning. 1991.**

The future of dynamically enforced contracts is ***static verification***!

Dynamic enforcement of program properties with software contracts

Formal verification
of program properties
Dynamic enforcement of program
properties with software contracts

```
@ ((Num)->Num, Num) -> Num
function f(g, x) {

   // y = ...

   return g(y)
}
```

```
@ ((Num)->Num, Num) -> Num
function f(g, x) {

   // y = ...

   return g(y)
}
```

Control-flow at `g(y)` **here...**

```
@ ((Num)->Num, Num) -> Num
function f(g, x) {

   // y = ...

   return g(y)
}
```

…and on the callers of `f`.

...depends on data-flow to `g`...

Control-flow at `g(y)` here...

```
f((n)=>n+1, 0)
f((n)=>n*n, 2)
```

```
@ ((Num)->Num, Num) -> Num
function f(g, x) {

   // y = ...

   return g(y)
}
```

…and on the callers of `f`.

...depends on data-flow to `g`...

Control-flow at `g(y)` here...

```
f((n)=>n+1, 0)
f((n)=>n*n, 2)
f(h, 0)
```

```
@ ((Num)->Num, Num) -> Num
function f(g, x) {

   // y = ...

   return g(y)
}
```

…and on the callers of `f`.

...depends on data-flow to `g`...

Control-flow at `g(y)` here...

Propagation
of program data/values

Propagation
of program control

This is called the

higher-order control-flow problem

$$\begin{tikzcd}
\textbf{Propagation of program data/values} \arrow[r, bend left, dashed, "\text{“depends upon”}"] & \textbf{Propagation of program control} \arrow[l, bend left, dashed, "\text{“depends upon”}"]
\end{tikzcd}$$

and to tackle this problem, we use

AI

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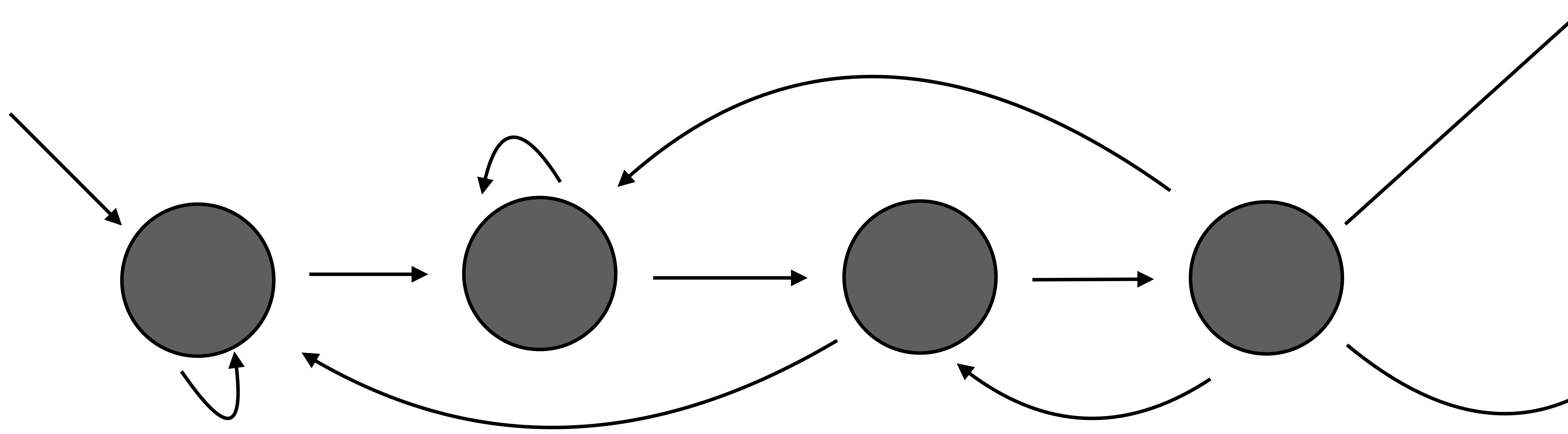
AI



Abstract **I**nterpretation

“Do you know the way?”

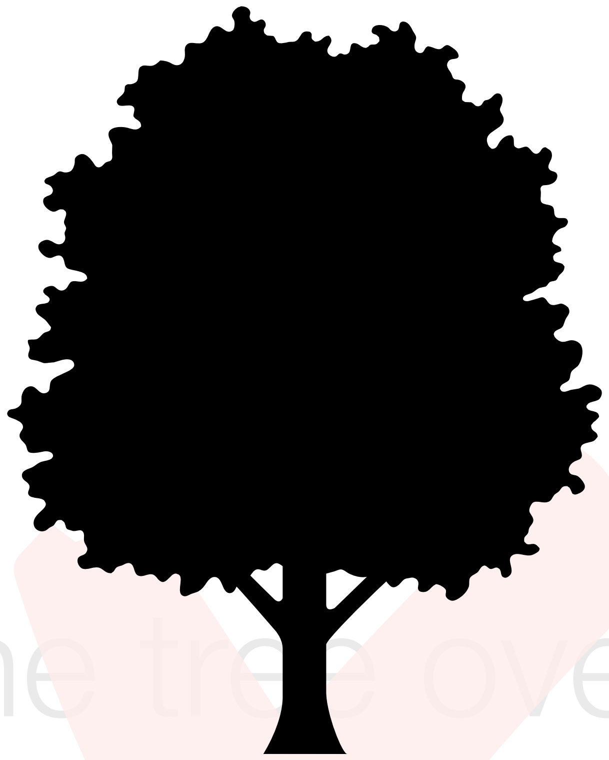
“Do you know the way?”

“Sure, you take a left just past that ***tree*** there.”

“The little poplar just there?”

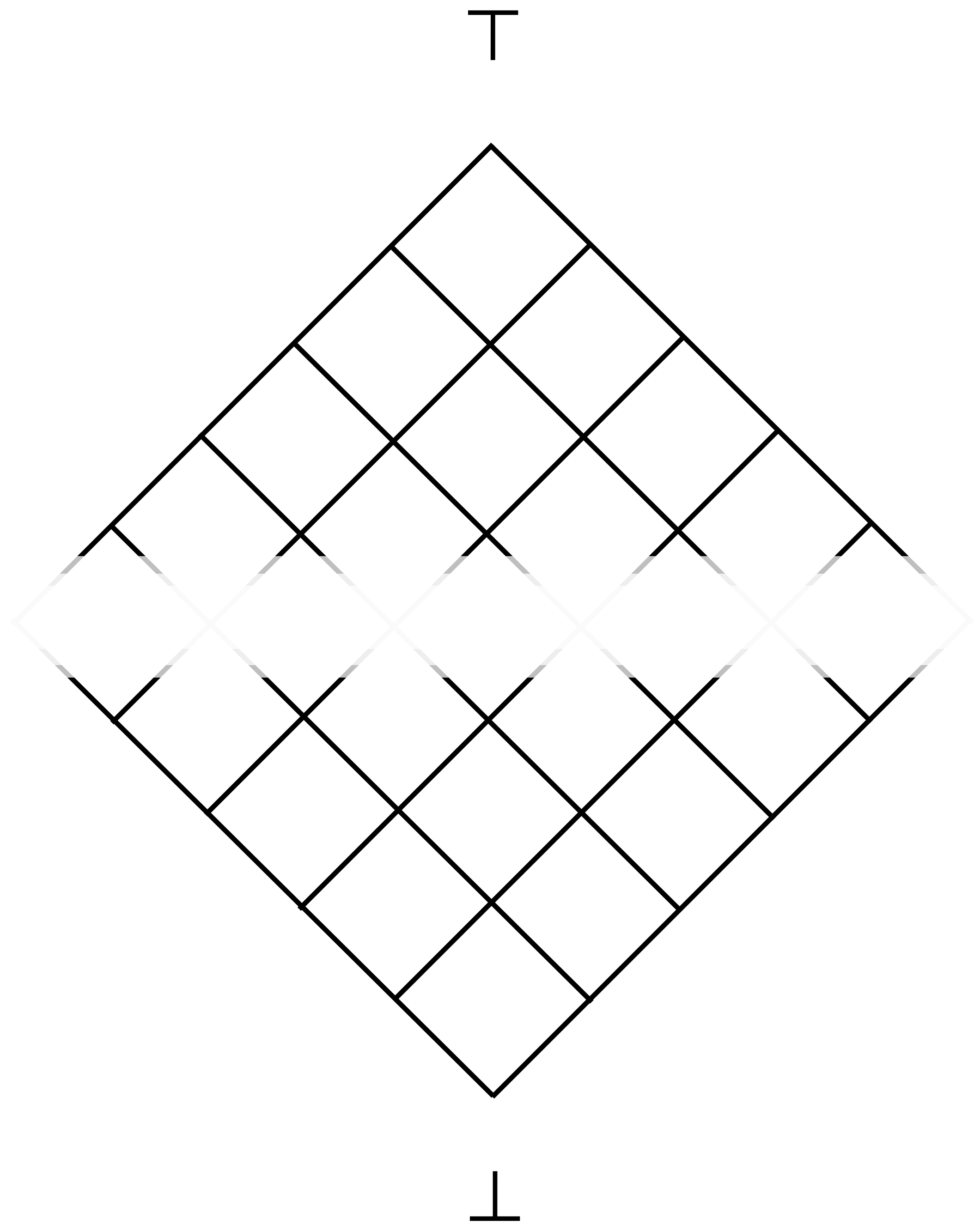
Ah no, the tree over *there*,
the ***one with 51 branches***
& 8206 leaves.

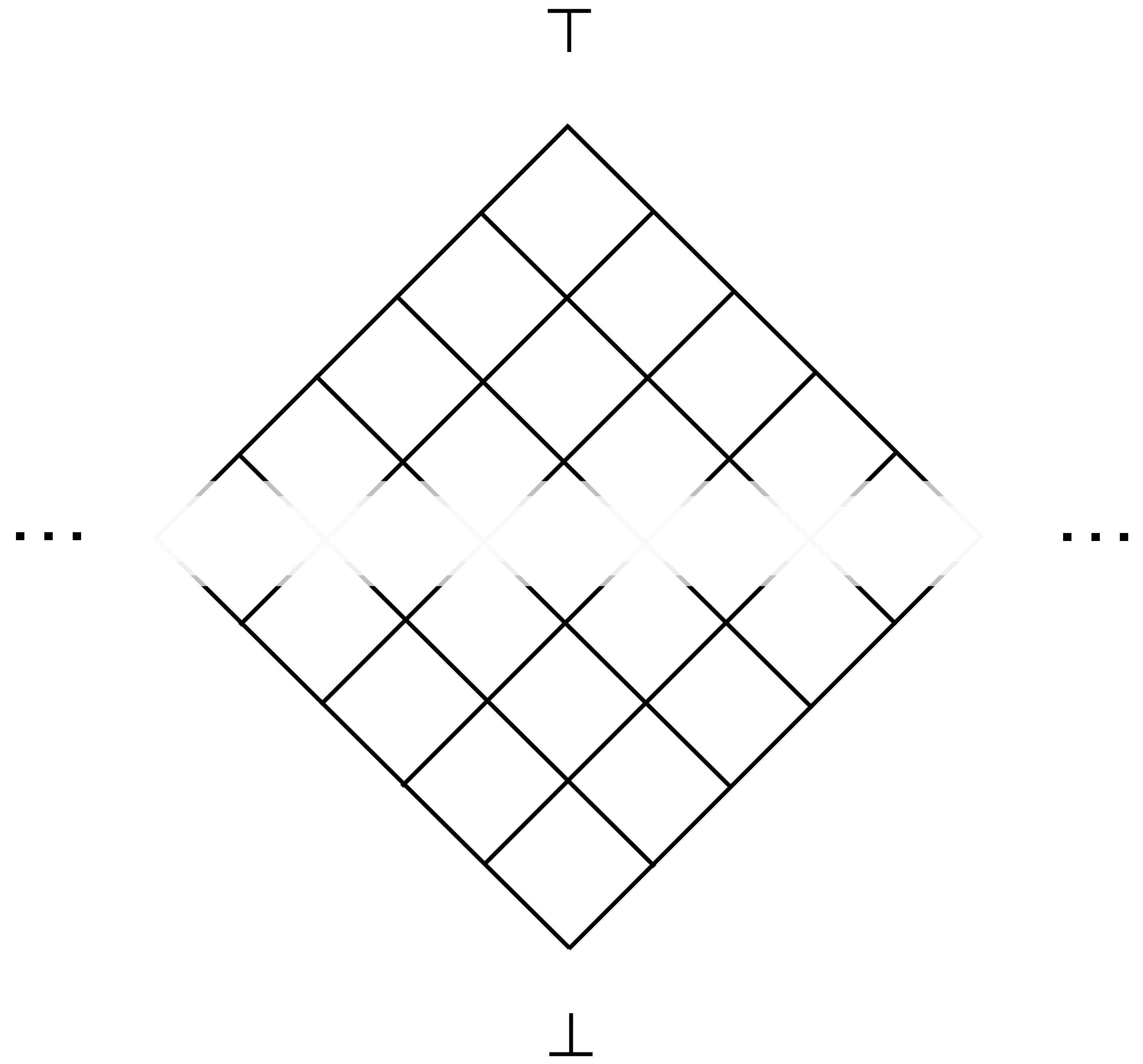
Ah no, the tree over *there*,
the ***one with 51 branches***
& 8206 leaves.

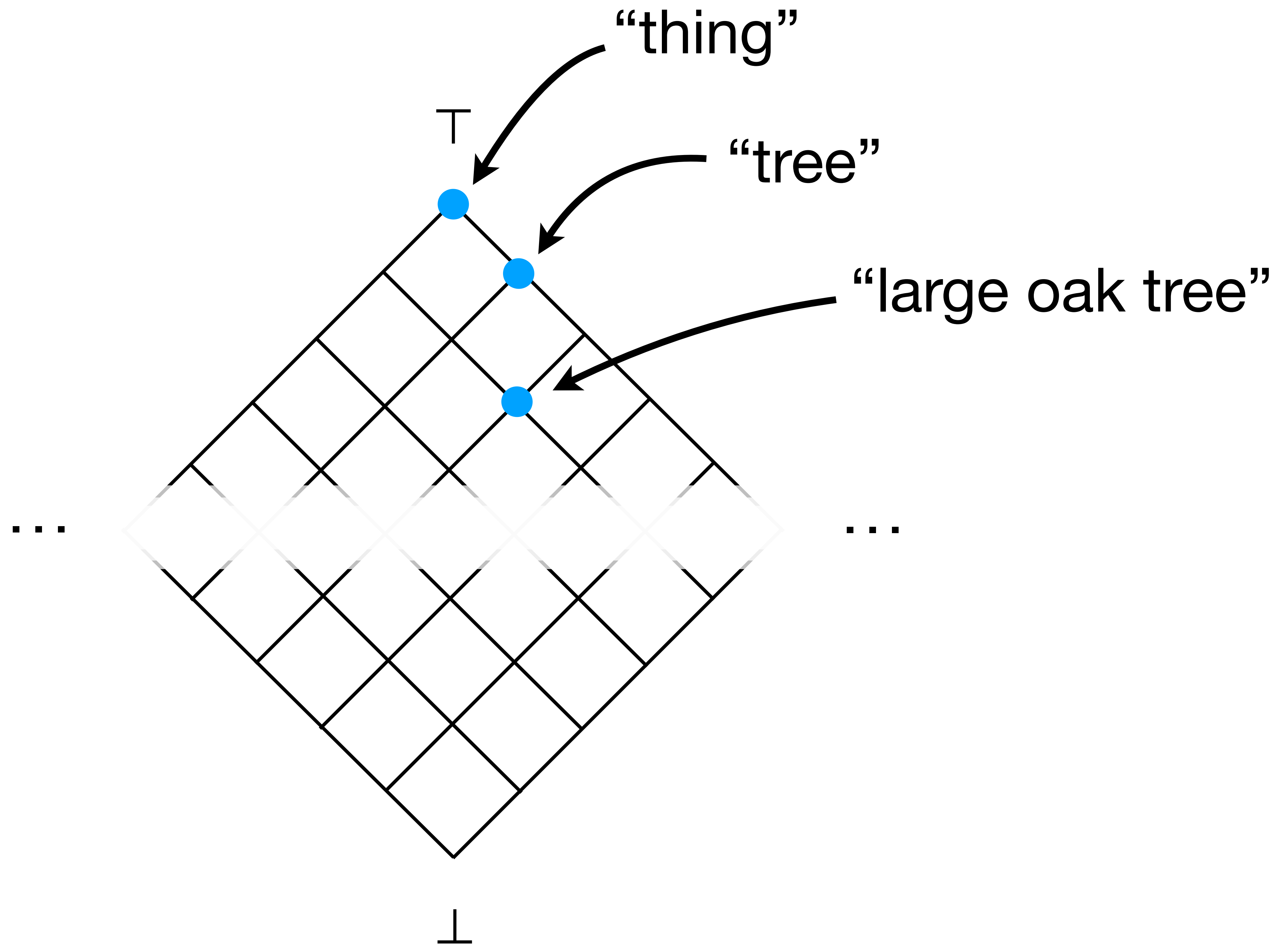


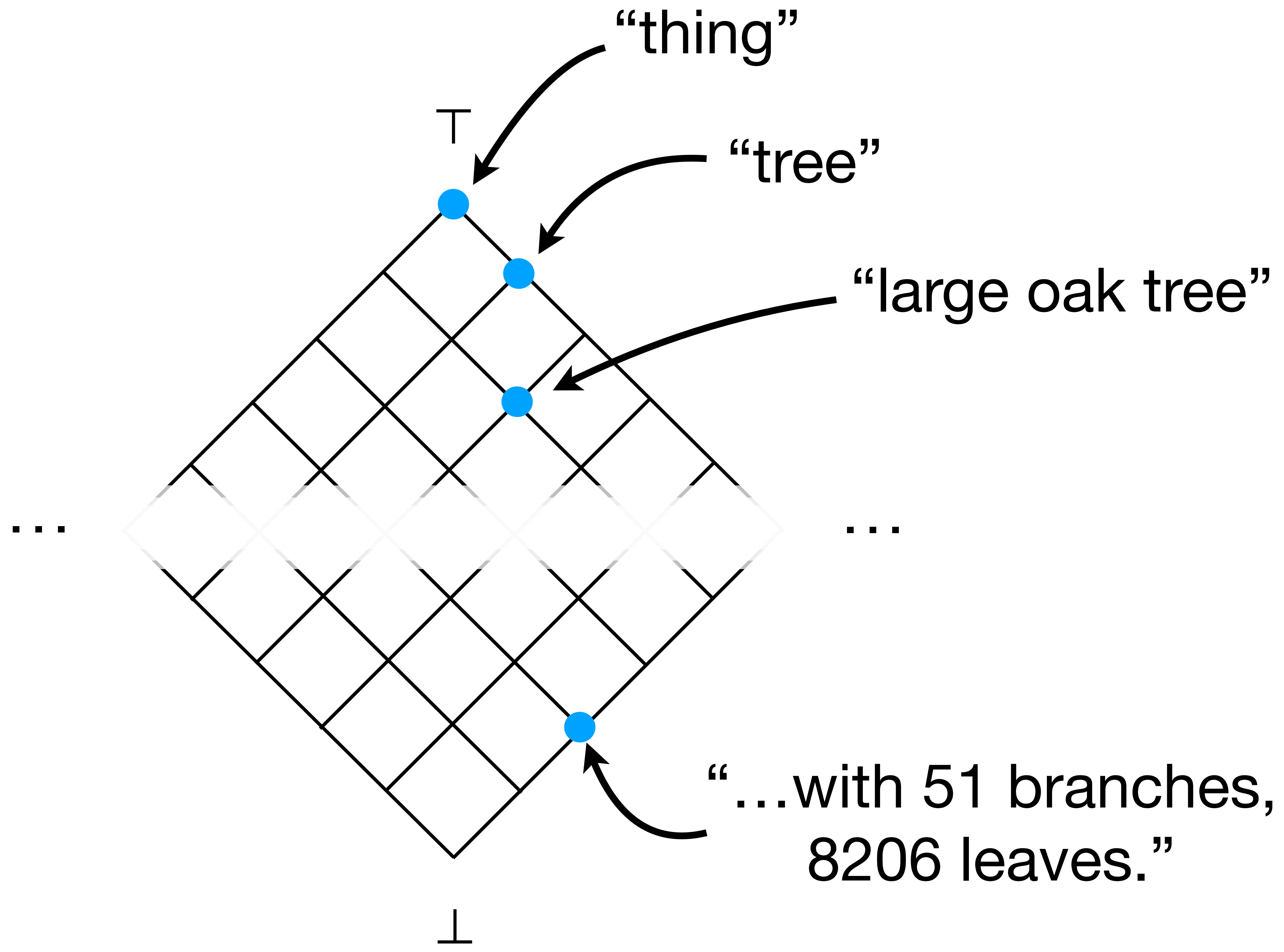
Ah no, the tree over *there*,
the ***one with 51 branches***
& 8260 leaves.

Ah no, the ***large oak tree*** there.

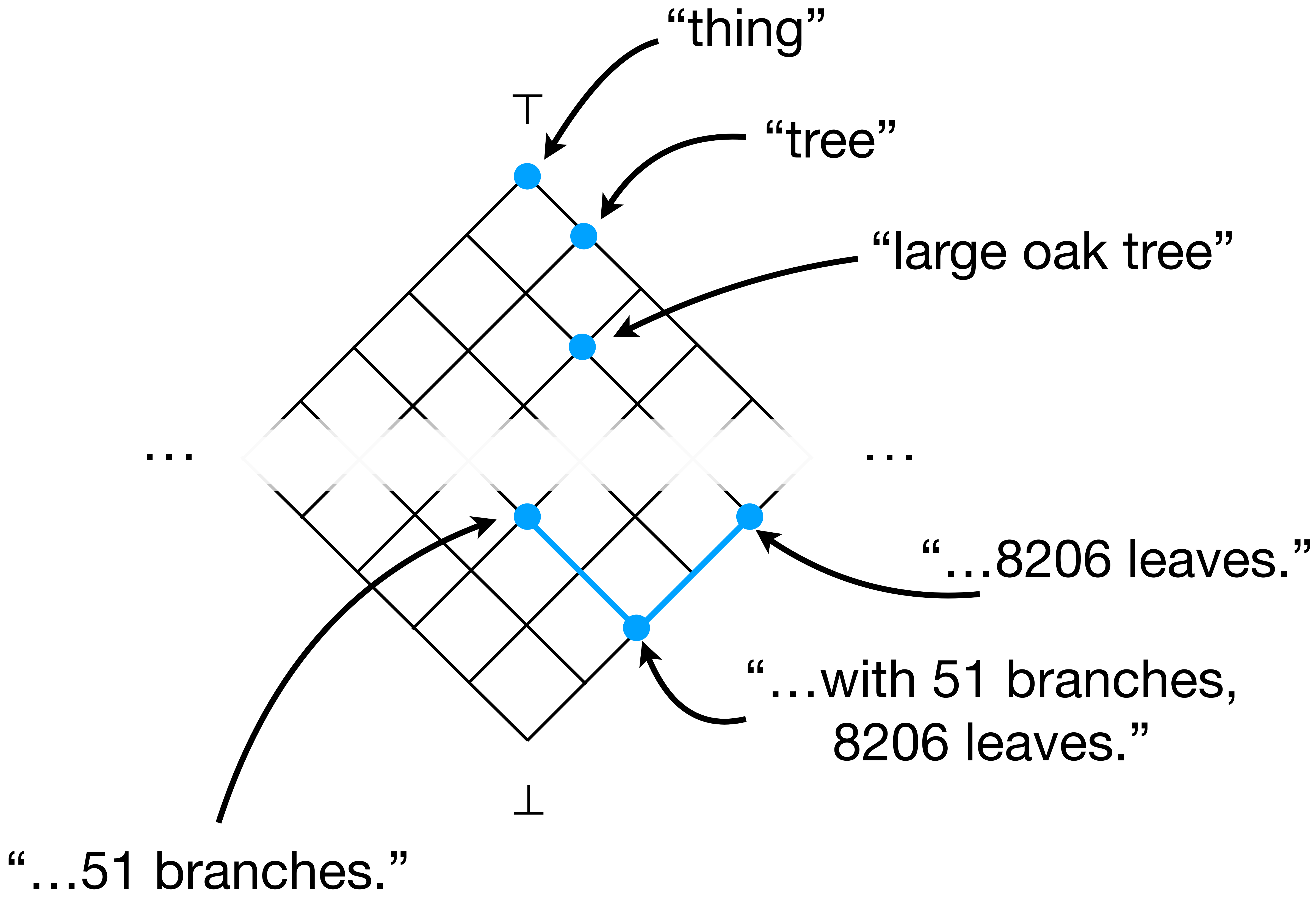

$\top$
$\bot$




"thing"
"tree"
"large oak tree"
⊤
⊥
…
…



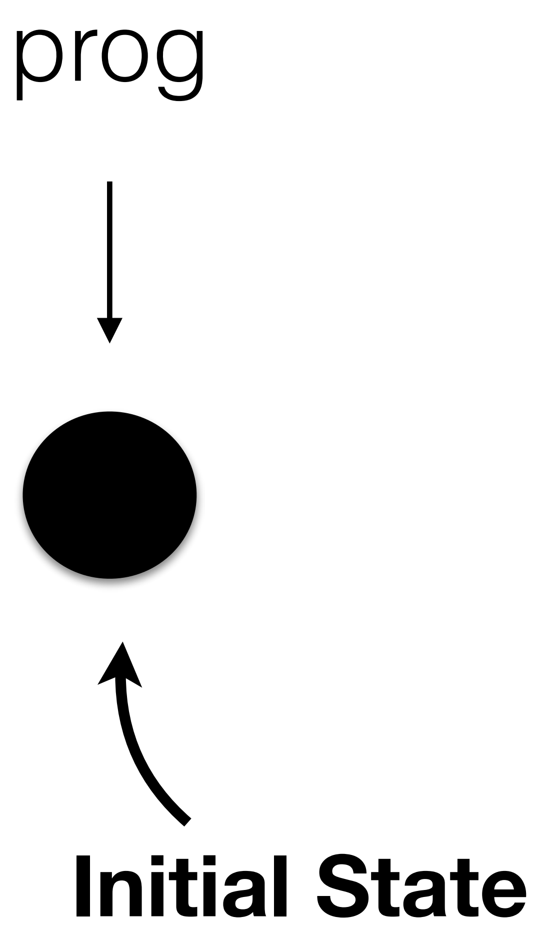
“thing”
⊤
“tree”
“large oak tree”
…
…
“…with 51 branches, 8206 leaves.”
⊥



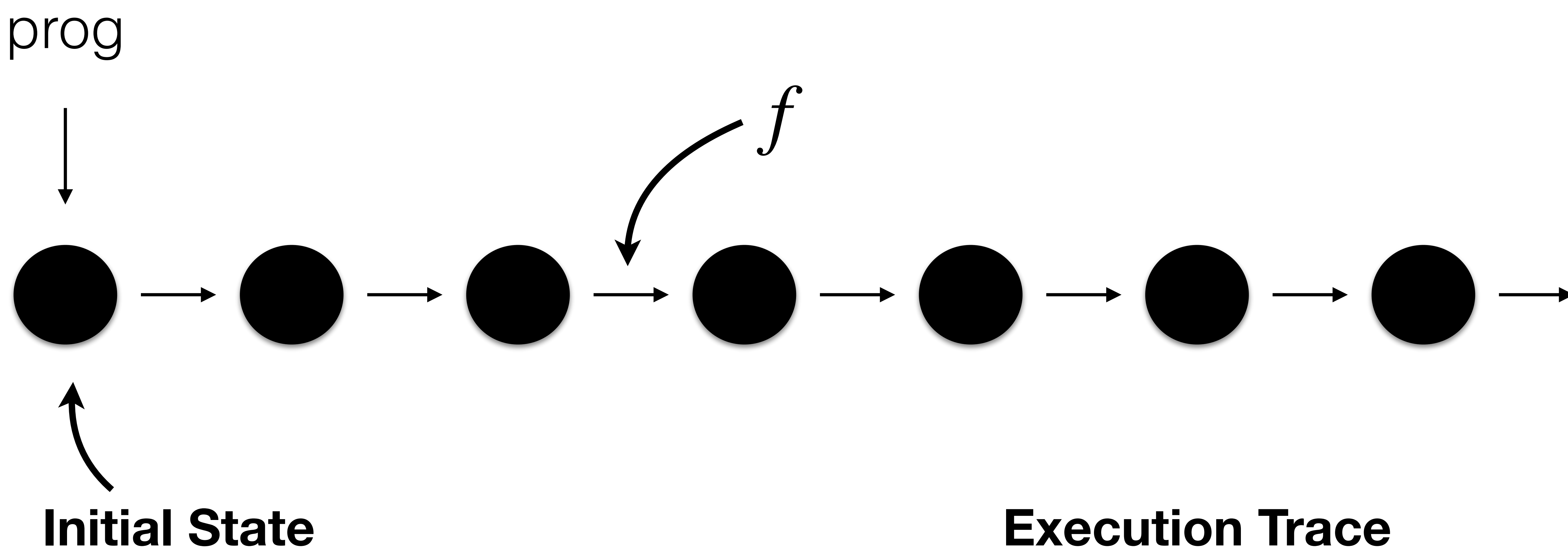
“thing”
⊤
“tree”
“large oak tree”
…
…
“…8206 leaves.”
“…with 51 branches, 8206 leaves.”
⊥
“…51 branches.”

prog

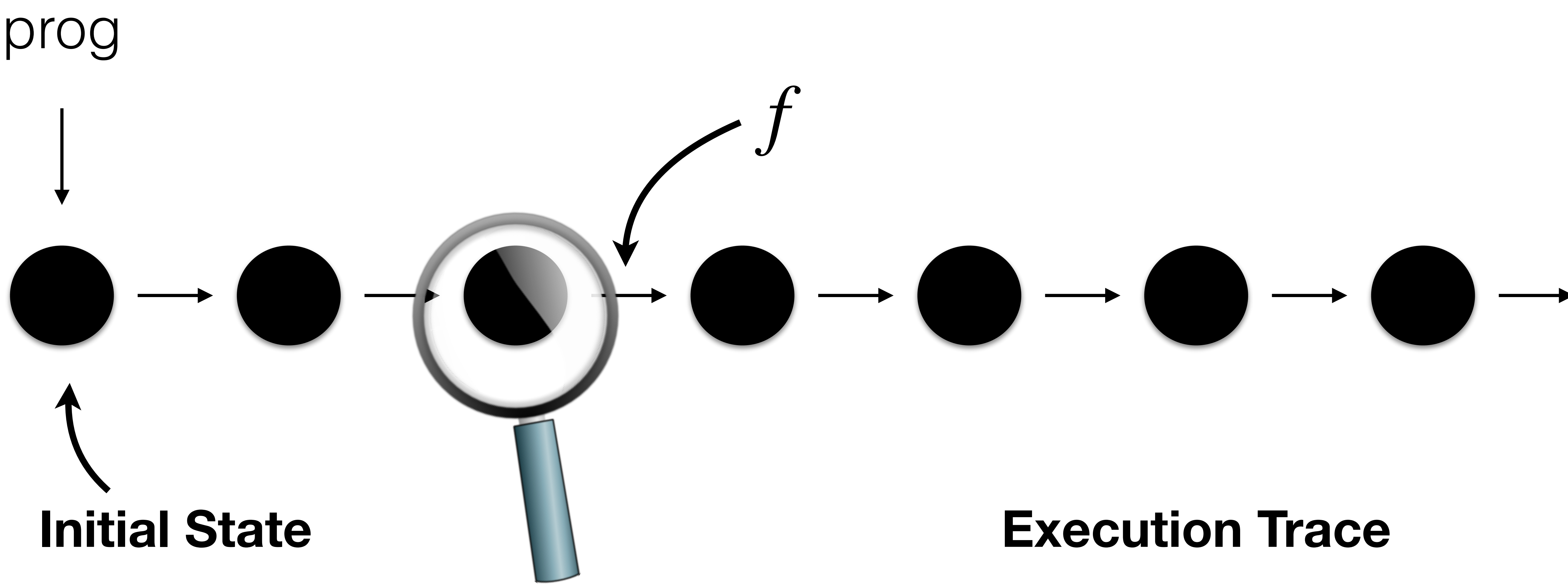
Plotkin (1981), Tarski (1955)



Plotkin (1981), Tarski (1955)



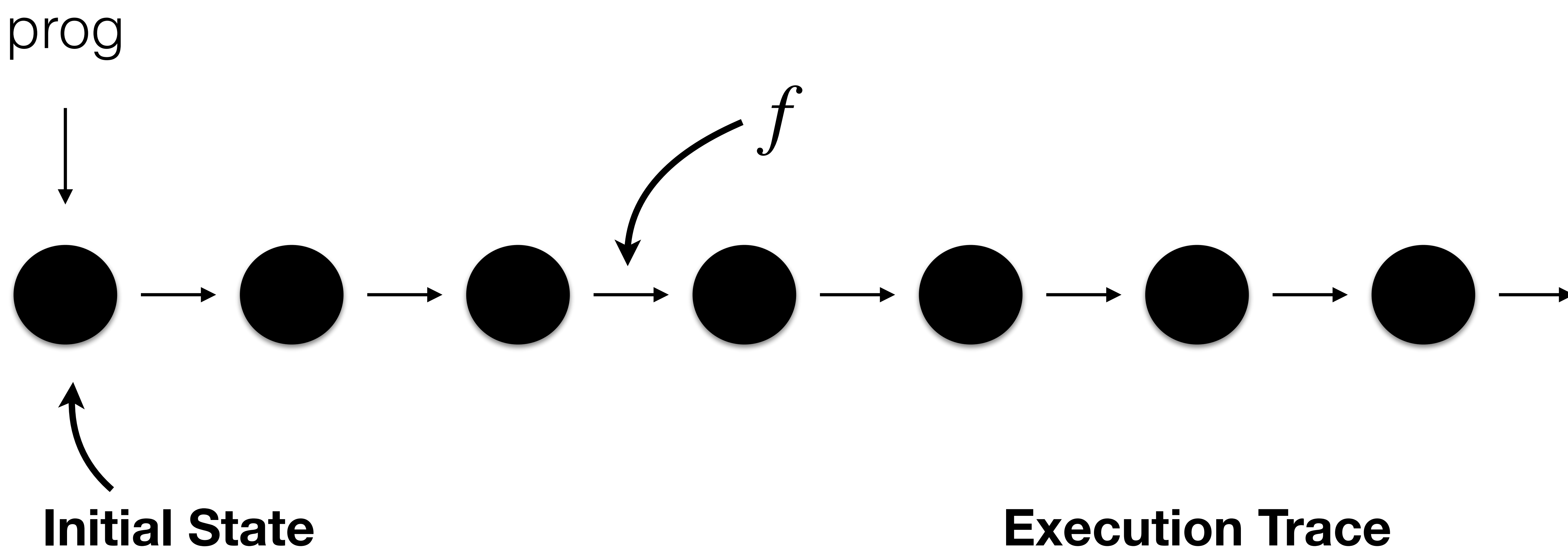
Plotkin (1981), Tarski (1955)



States may contain:
- the program counter,
- a binding environment,
- a model of the heap,
- a model of the stack,

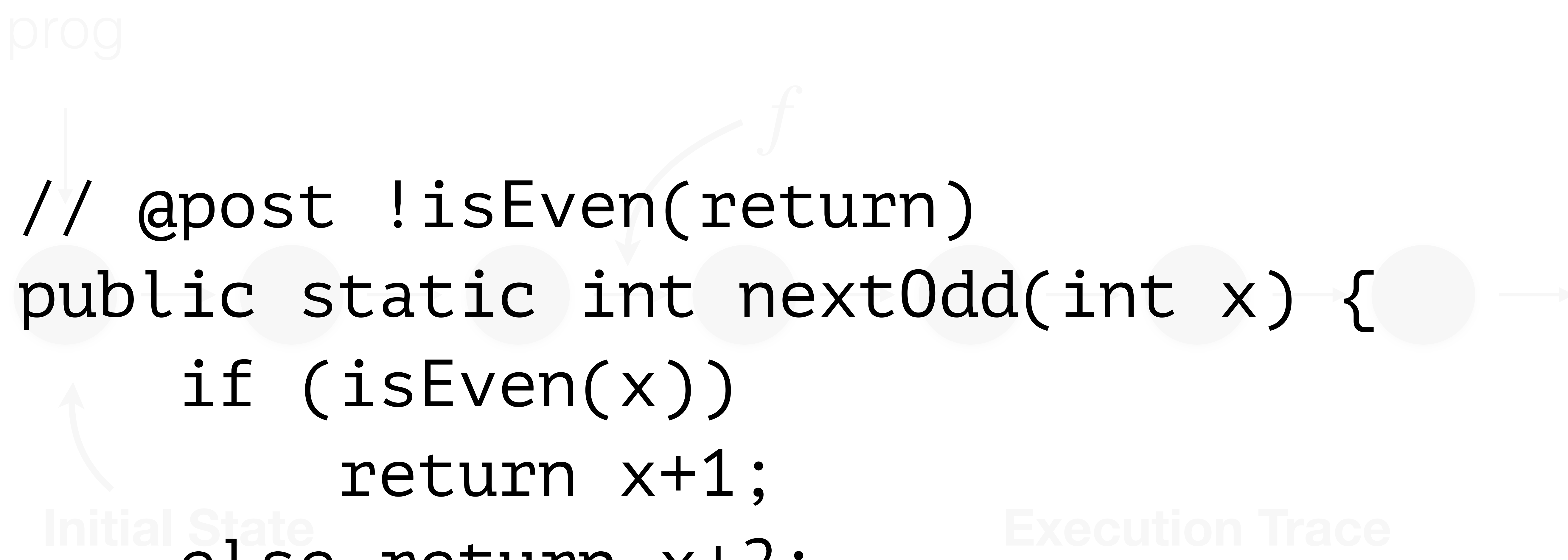
etc…

Plotkin (1981), Tarski (1955)

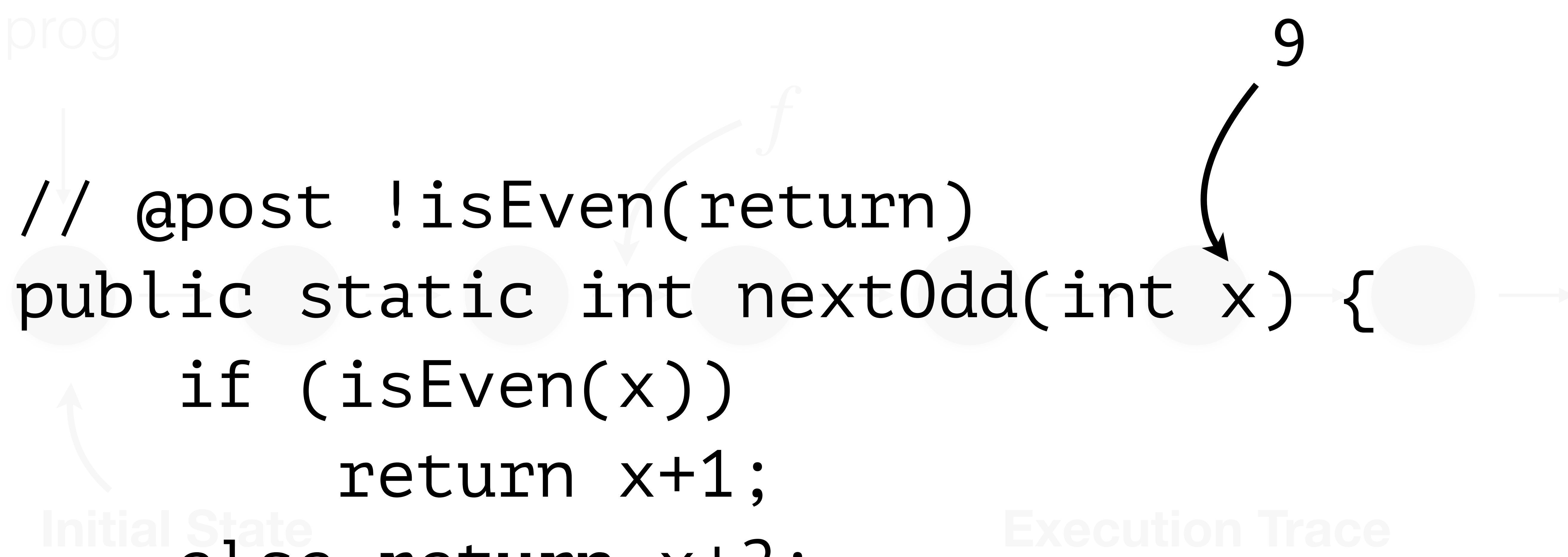


Plotkin (1981), Tarski (1955)

```
// @post !isEven(return)
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```



Plotkin (1981), Tarski (1955)

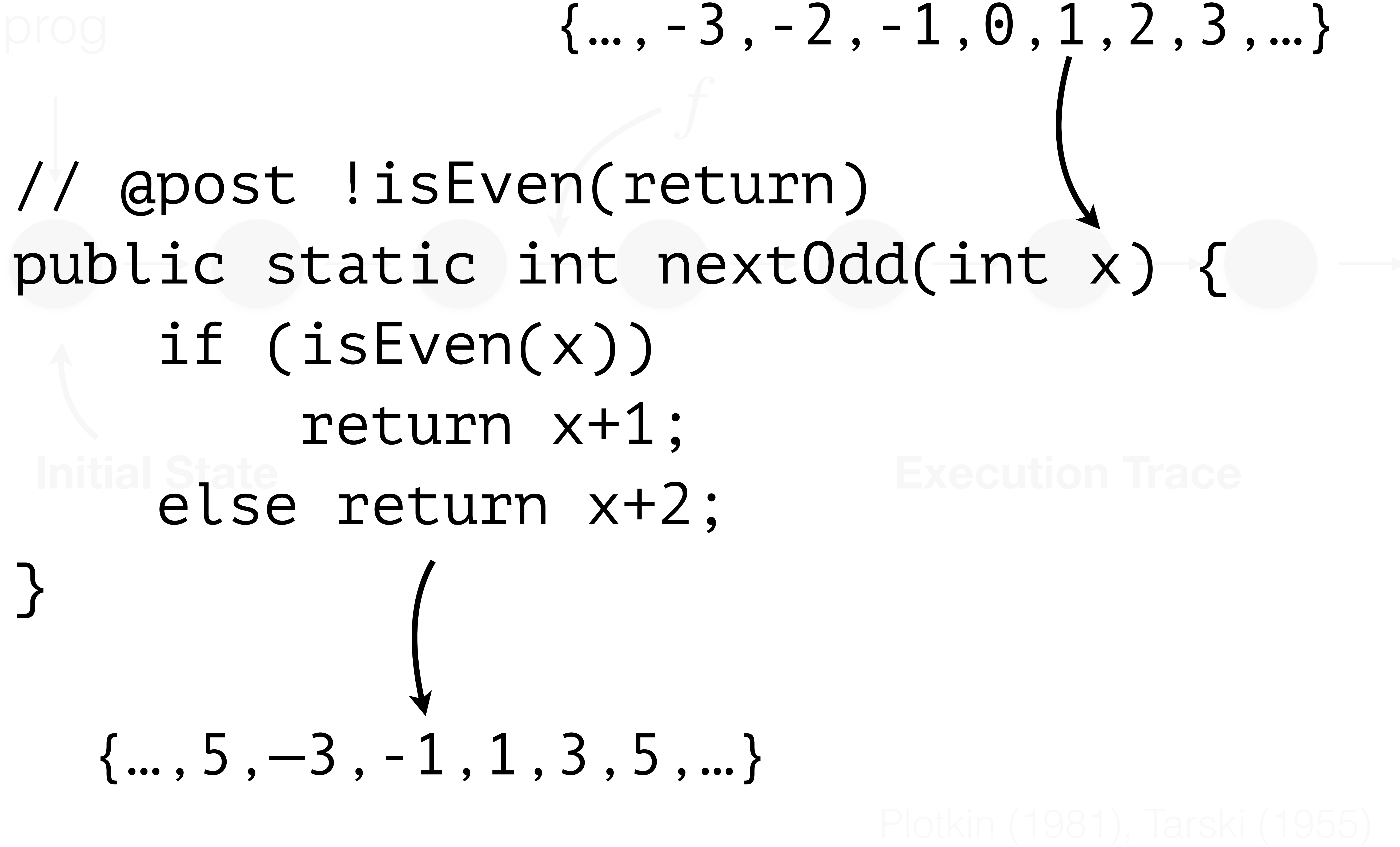


9

```
// @post !isEven(return)
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```

11

Plotkin (1981), Tarski (1955)

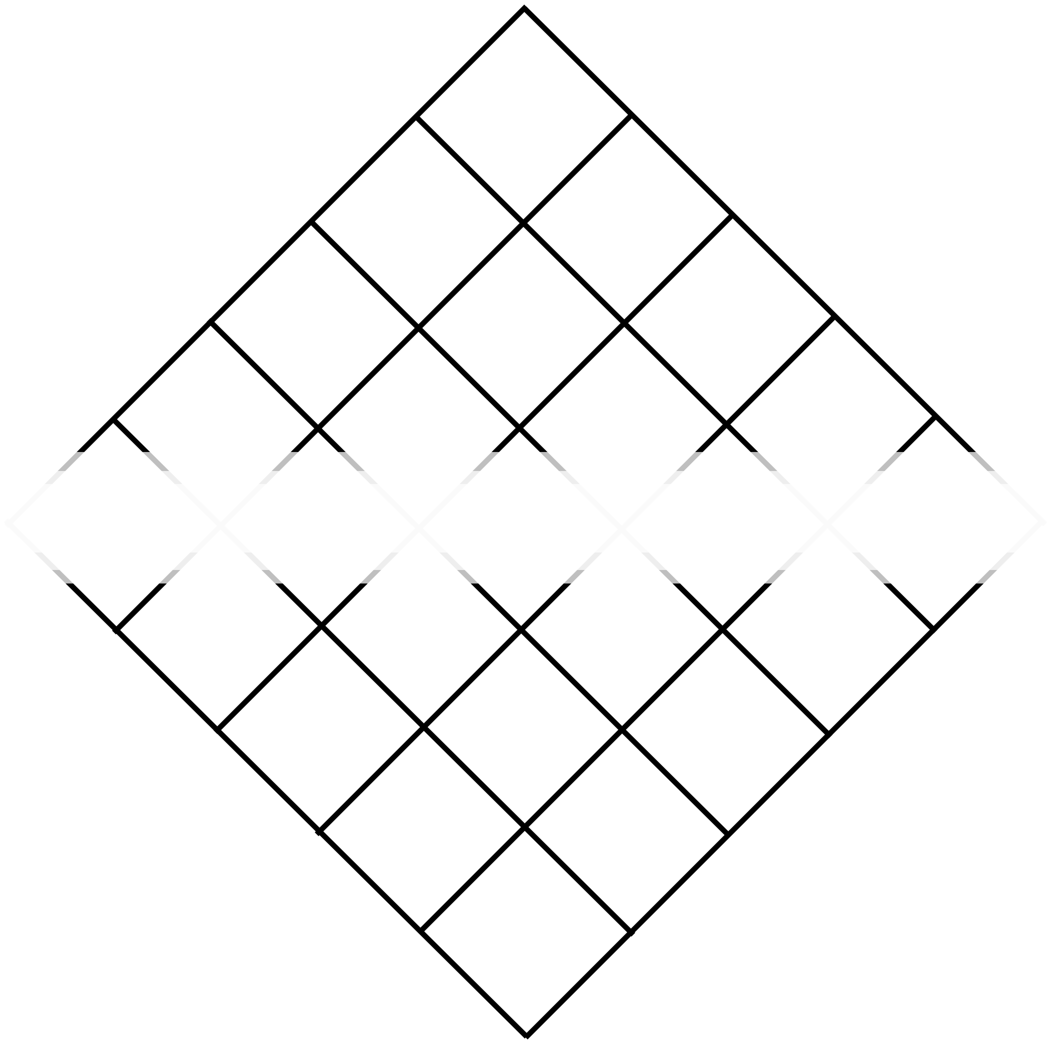


{…,-3,-2,-1,0,1,2,3,…}

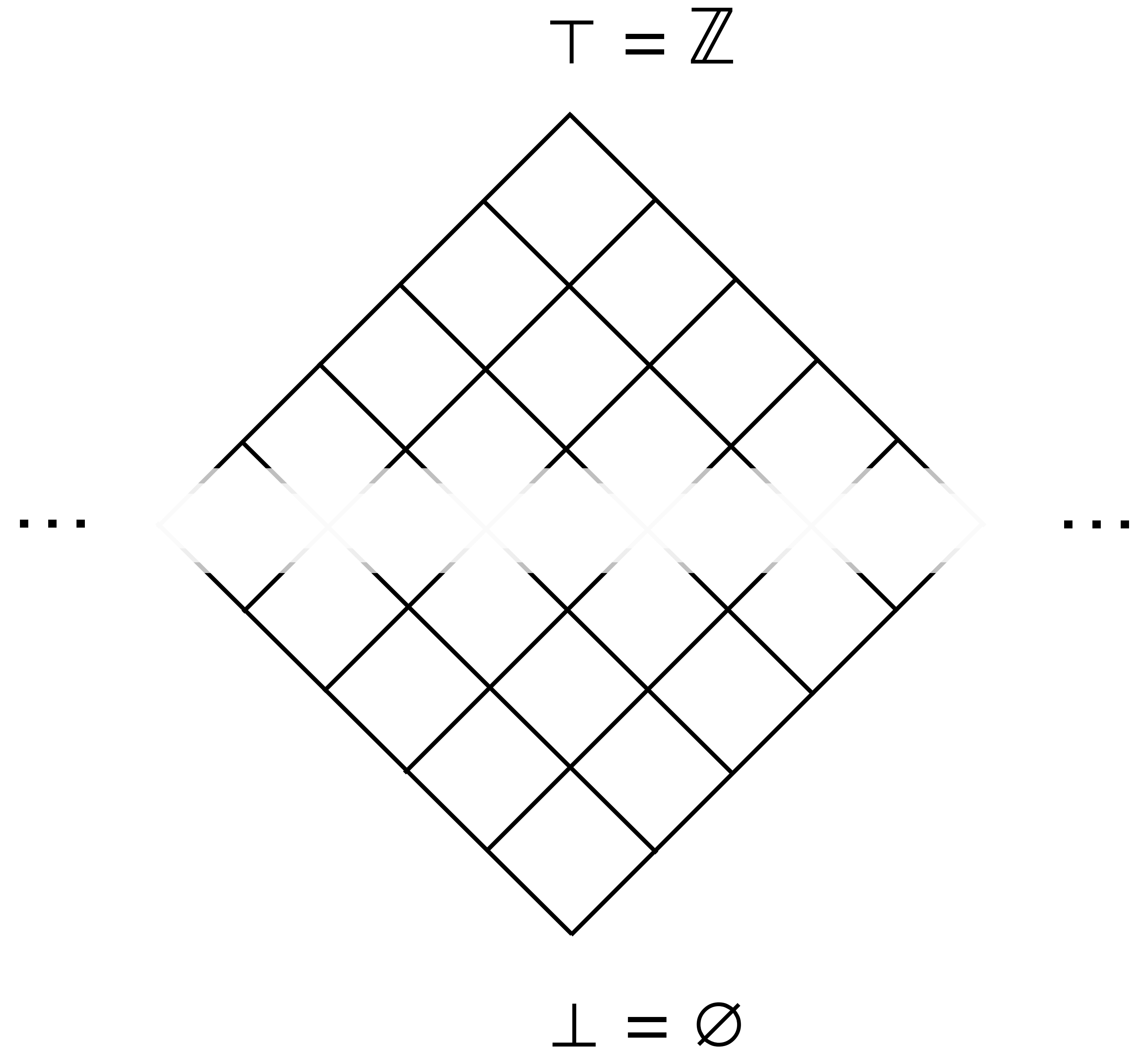
```
// @post !isEven(return)
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```

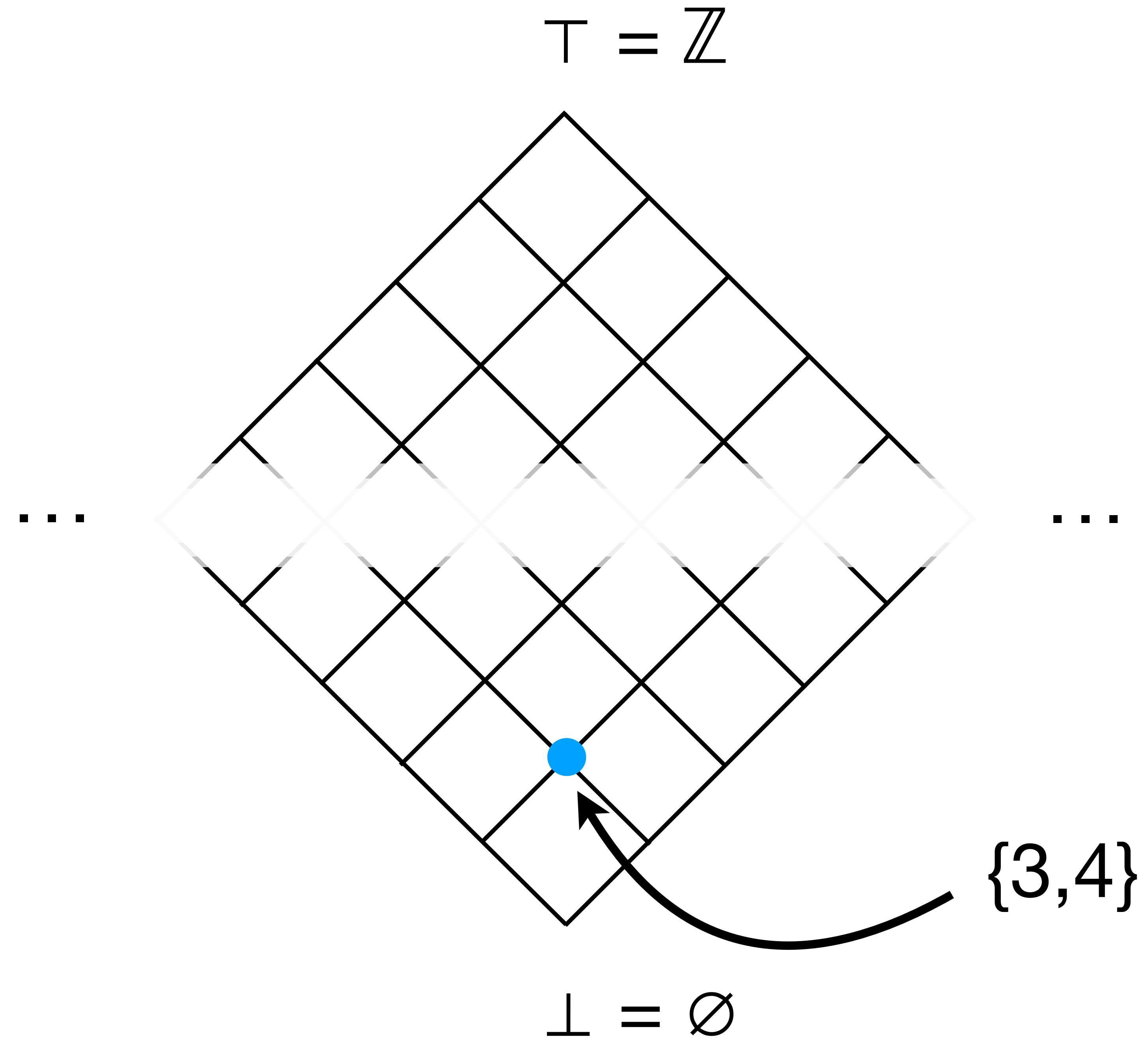
{…,5,—3,-1,1,3,5,…}

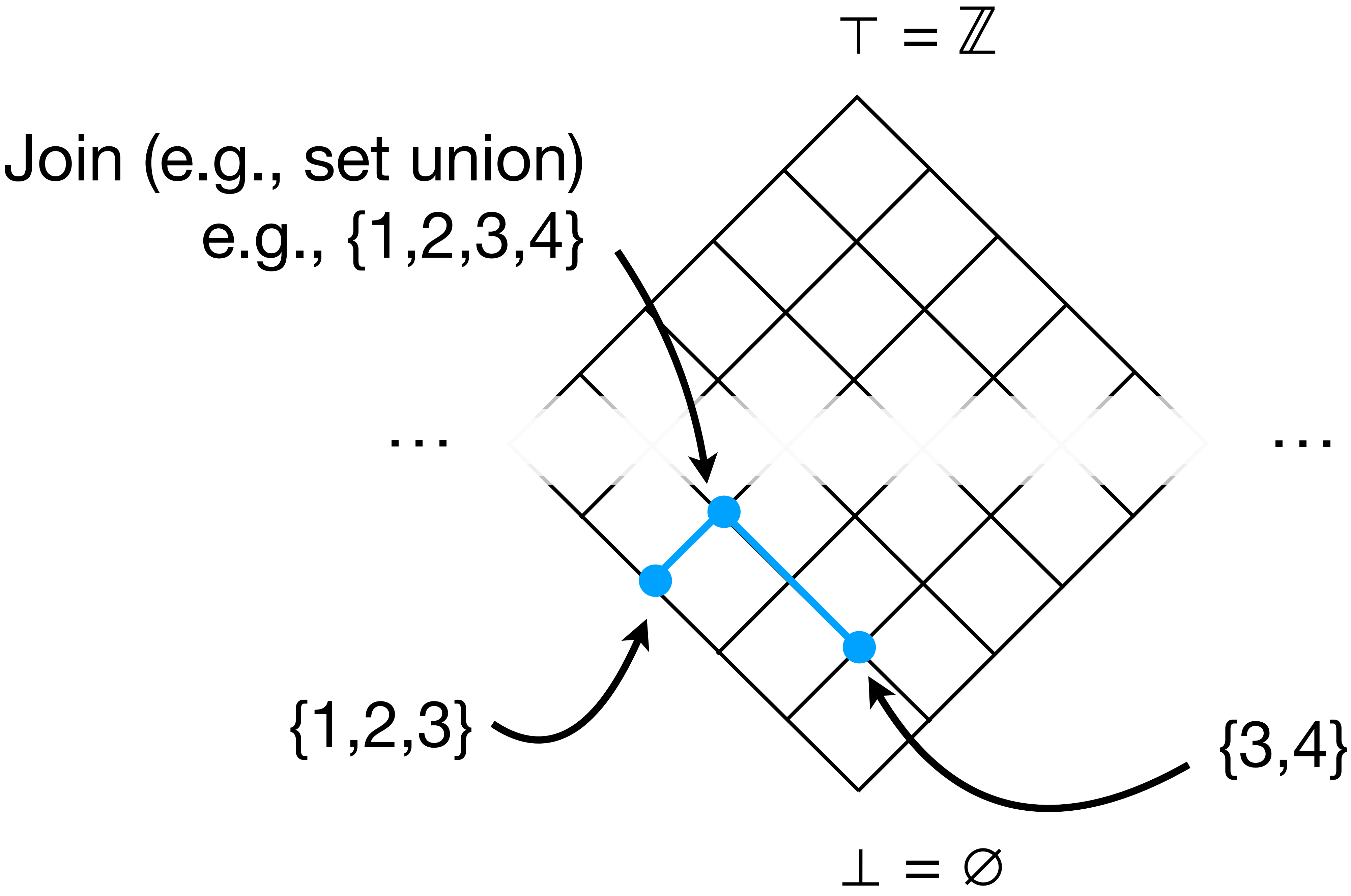
$\top = \mathbb{Z}$



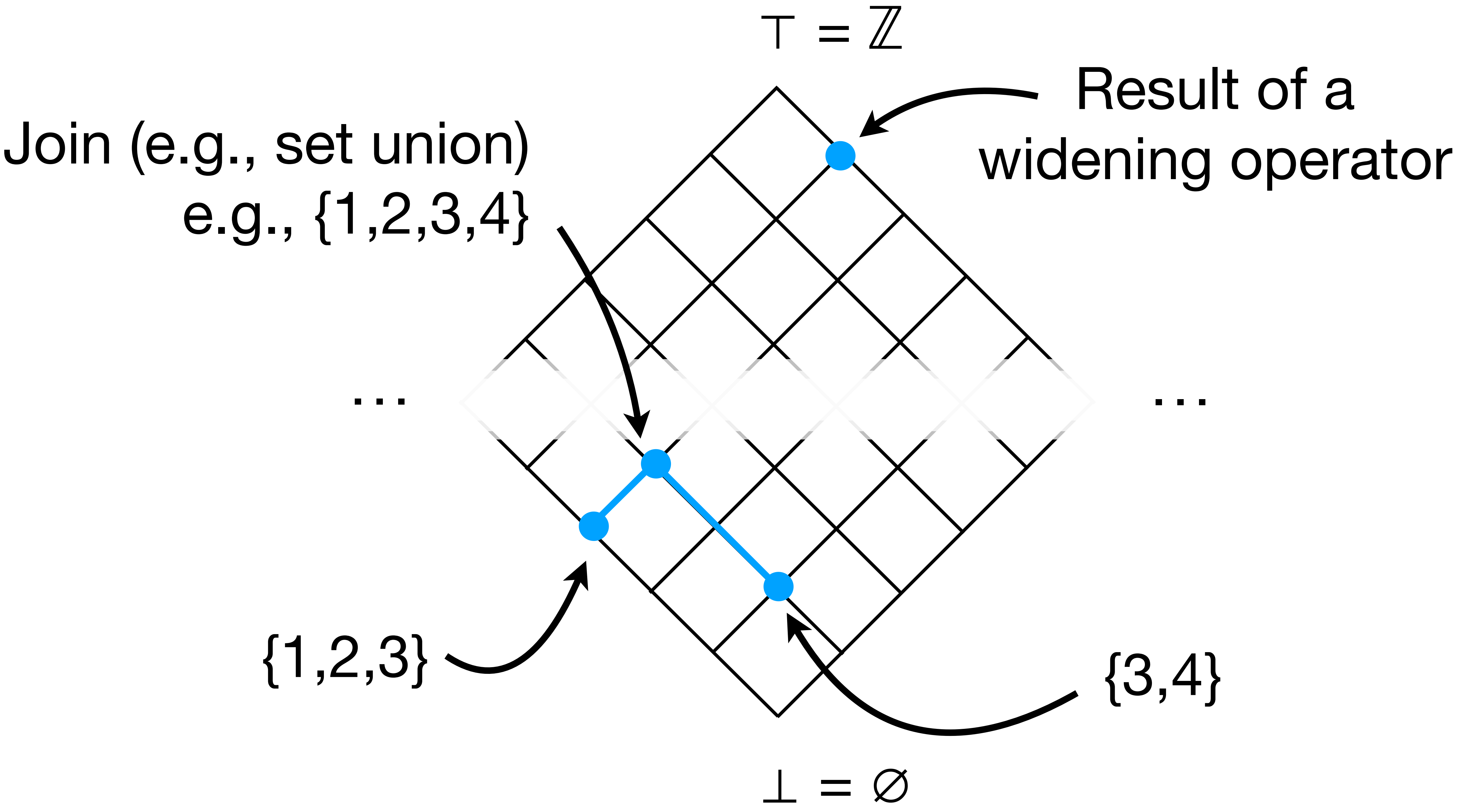
$\bot = \emptyset$


⊤ = ℤ
…
…
⊥ = ∅


⊤ = ℤ
…
…
{3,4}
⊥ = ∅

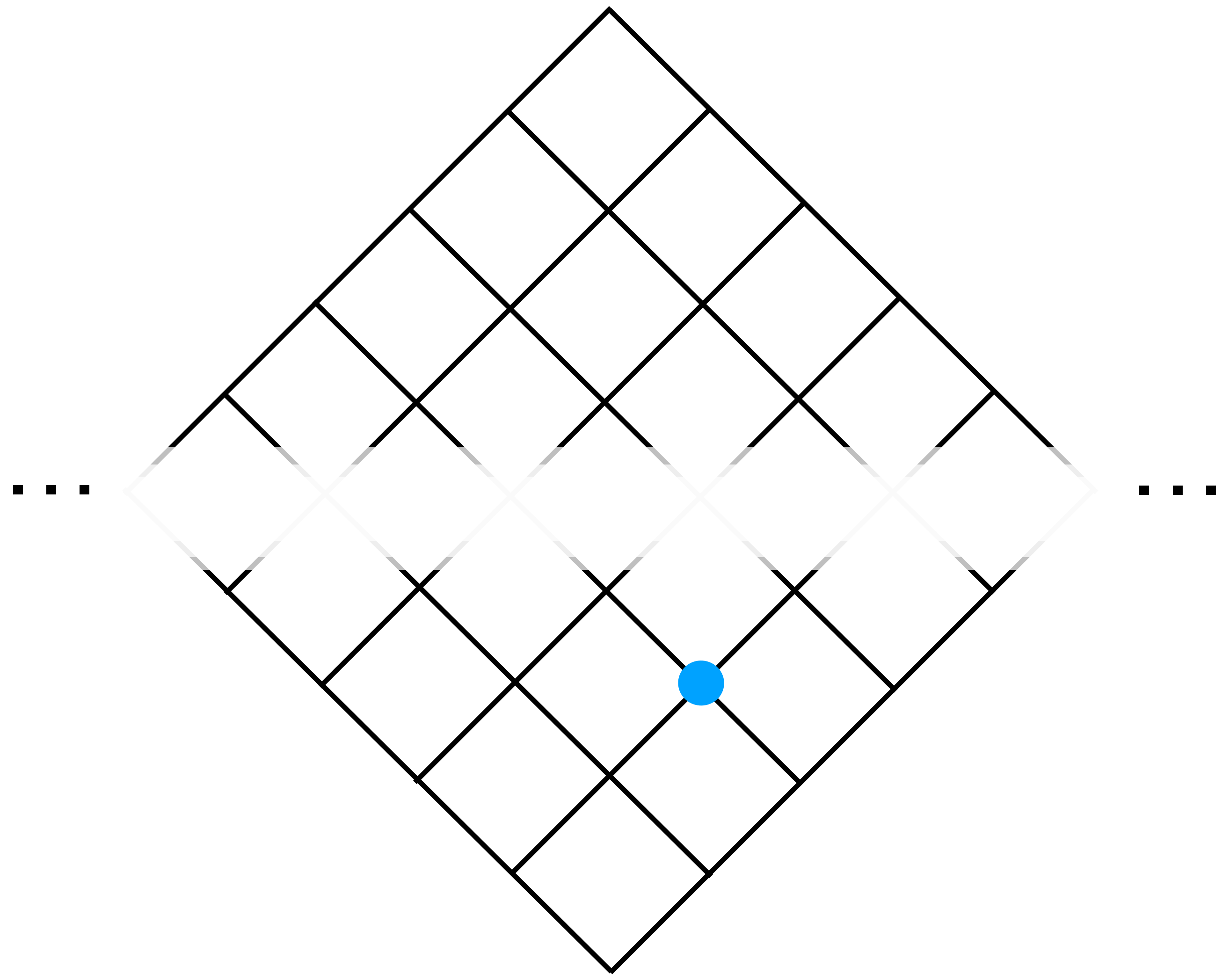


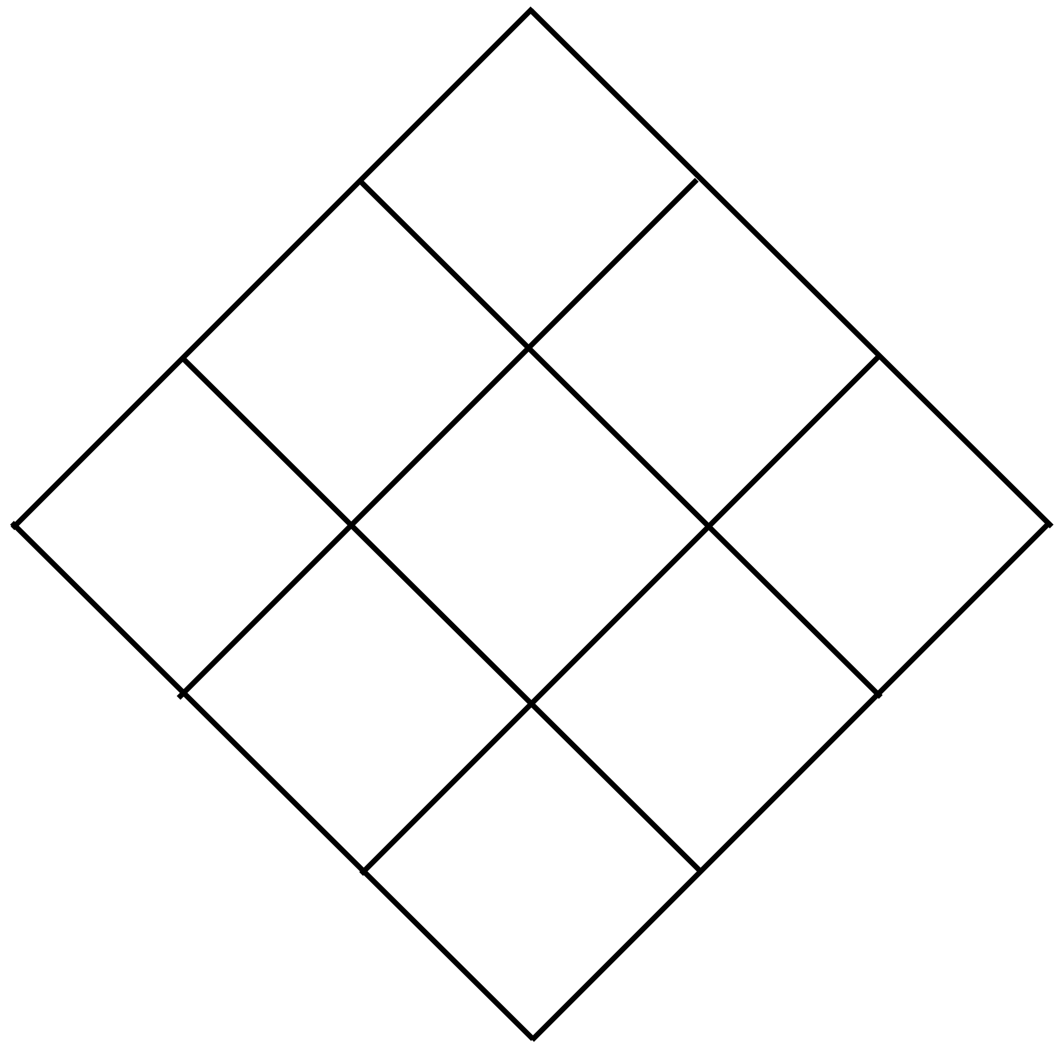
⊤ = ℤ
Join (e.g., set union)
e.g., {1,2,3,4}
…
…
{1,2,3}
{3,4}
⊥ = ∅

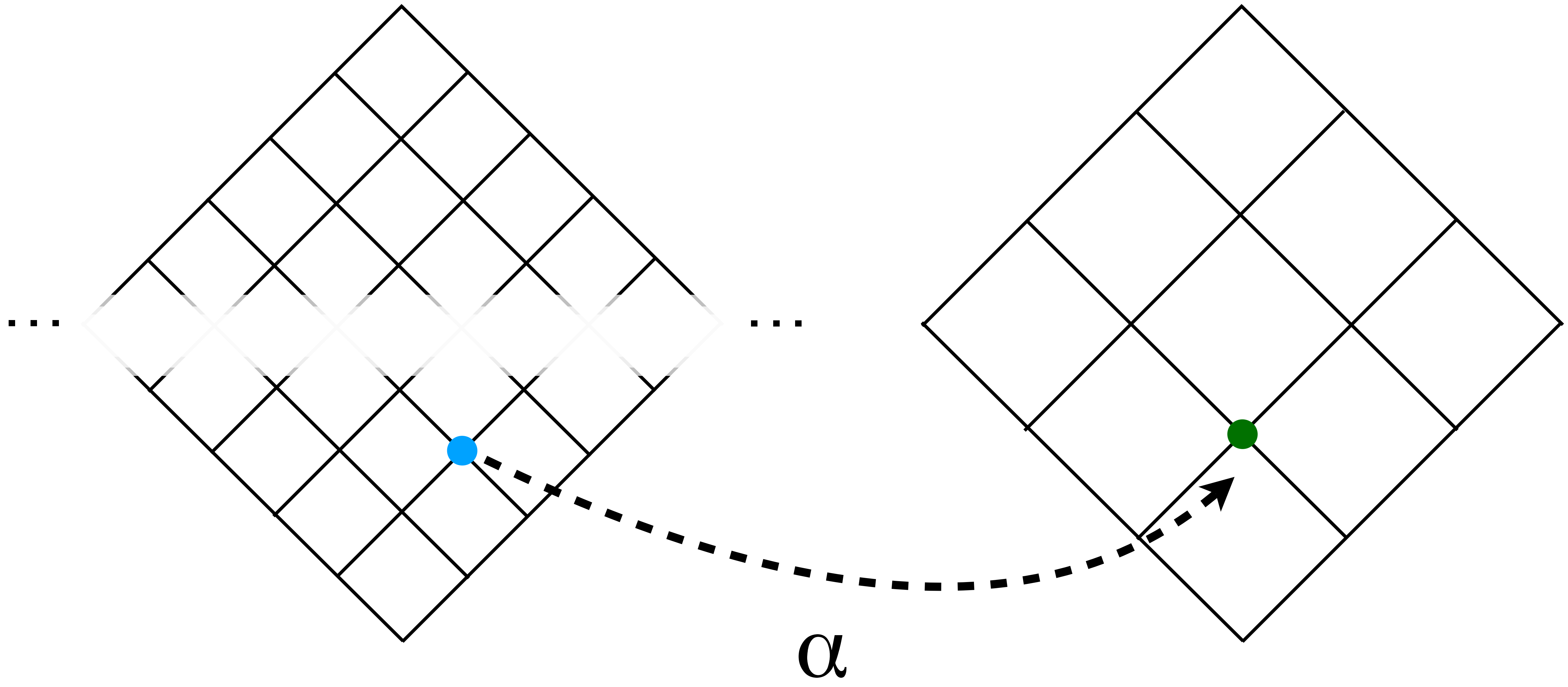


⊤ = ℤ
Result of a widening operator
Join (e.g., set union) e.g., {1,2,3,4}
…
…
{1,2,3}
{3,4}
⊥ = ∅

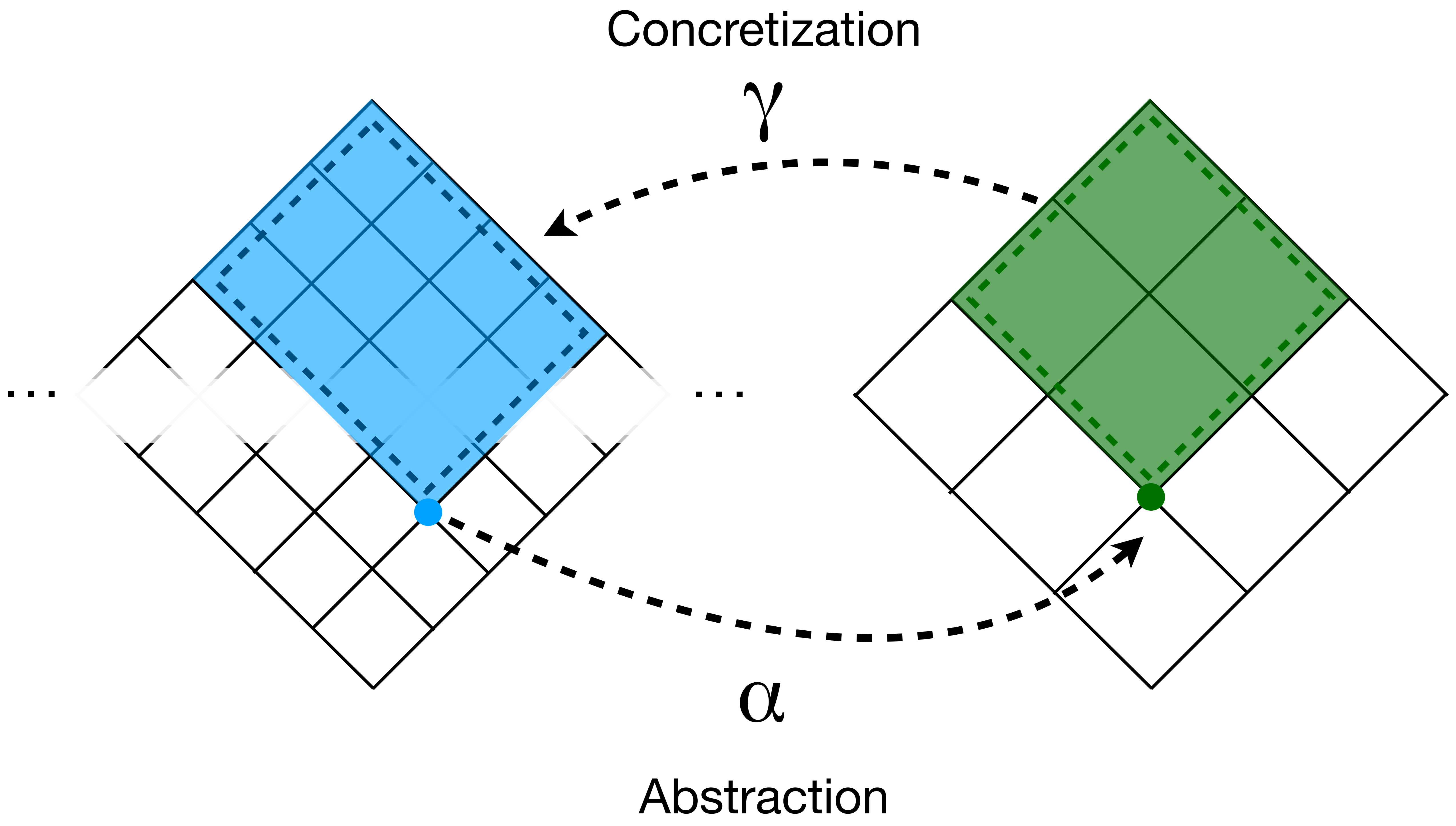
$$\begin{tikzcd}
 & \top = \{\textbf{Even, Odd}\} \arrow[dl, no head] \arrow[dr, no head] & \\
\{\textbf{Odd}\} \arrow[dr, no head] & & \{\textbf{Even}\} \arrow[dl, no head] \\
 & \bot = \varnothing &
\end{tikzcd}$$







Abstraction

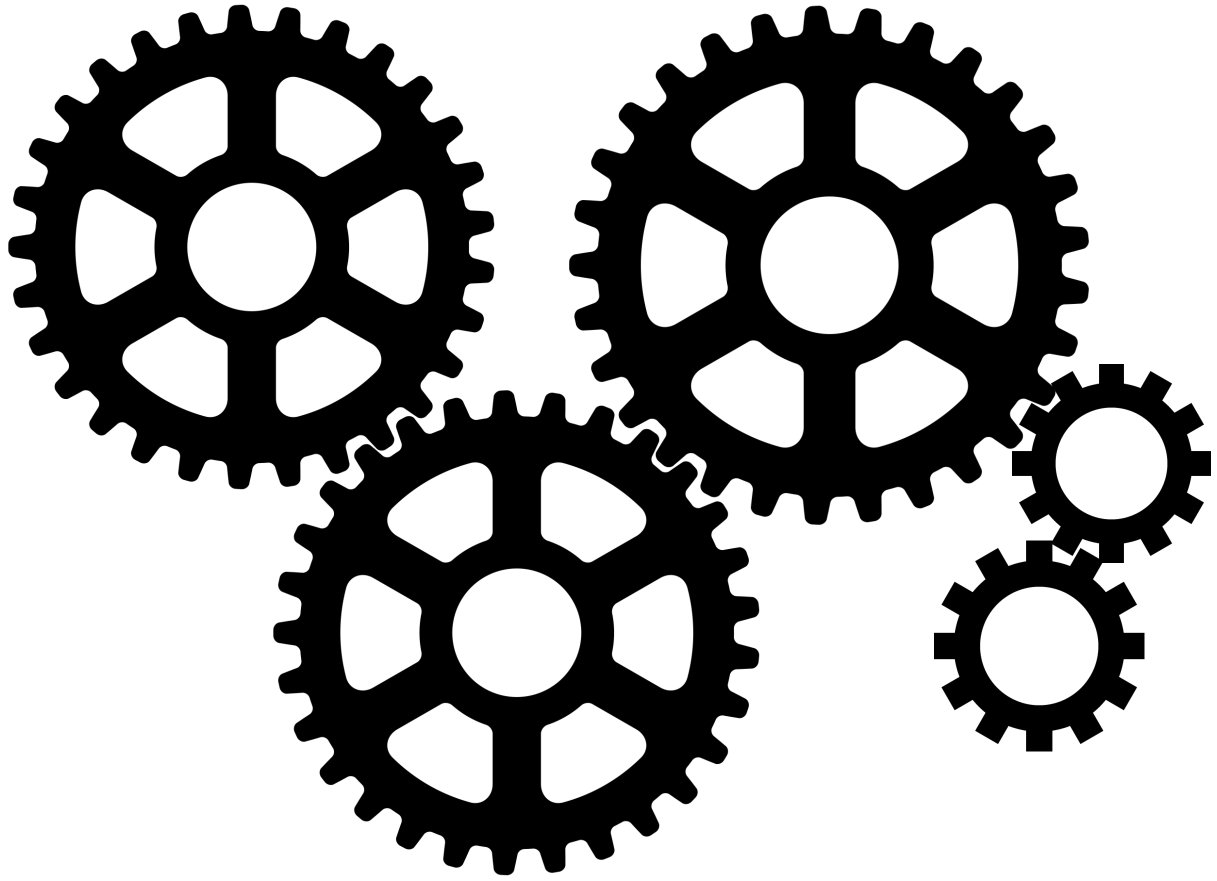


Galois connection

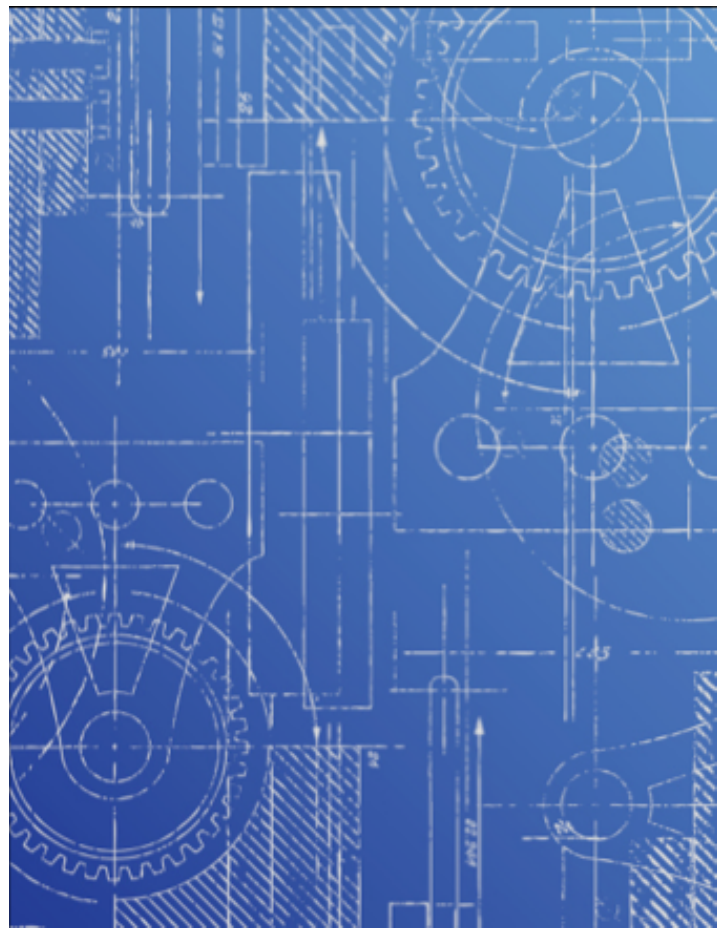
$$\alpha(c) \sqsubseteq a \iff c \sqsubseteq \gamma(a)$$

Concrete Interpreter

Abstraction Specification



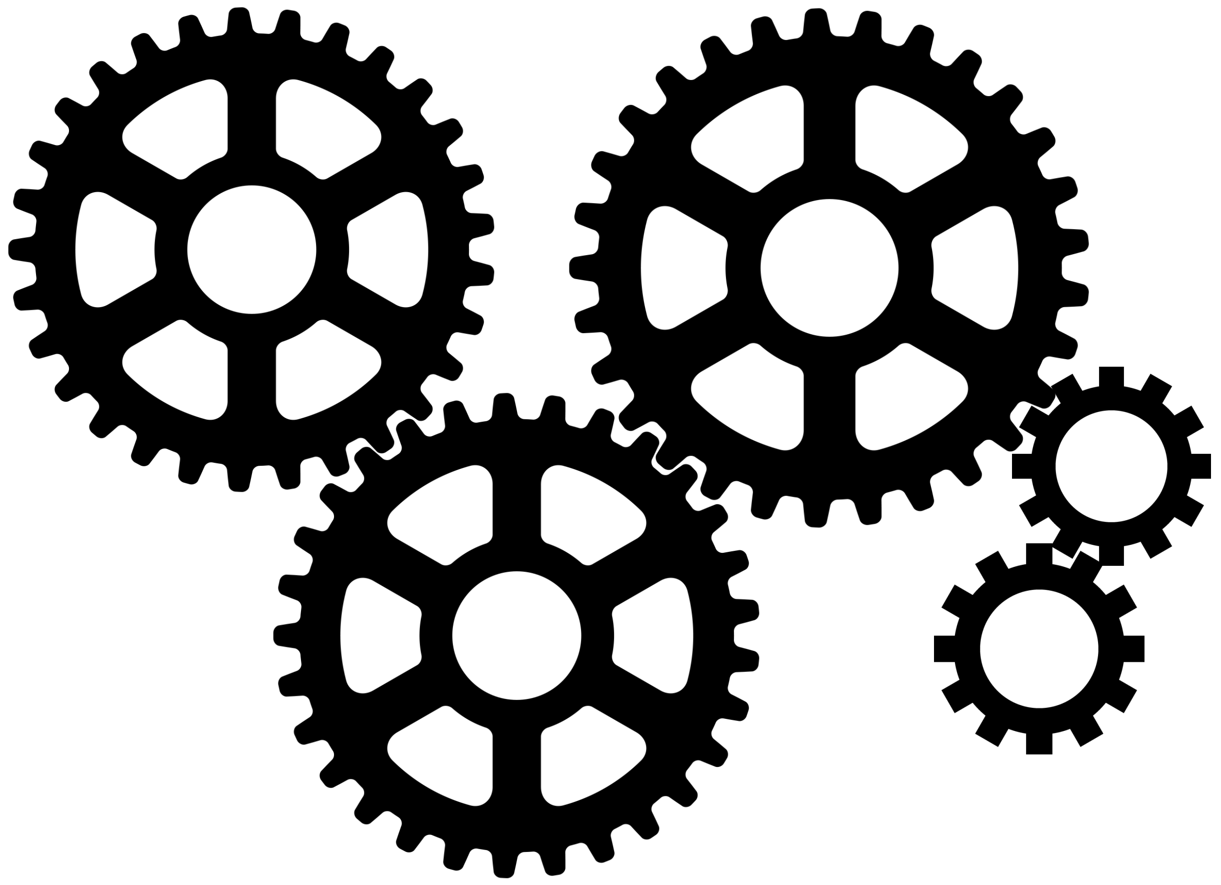
+



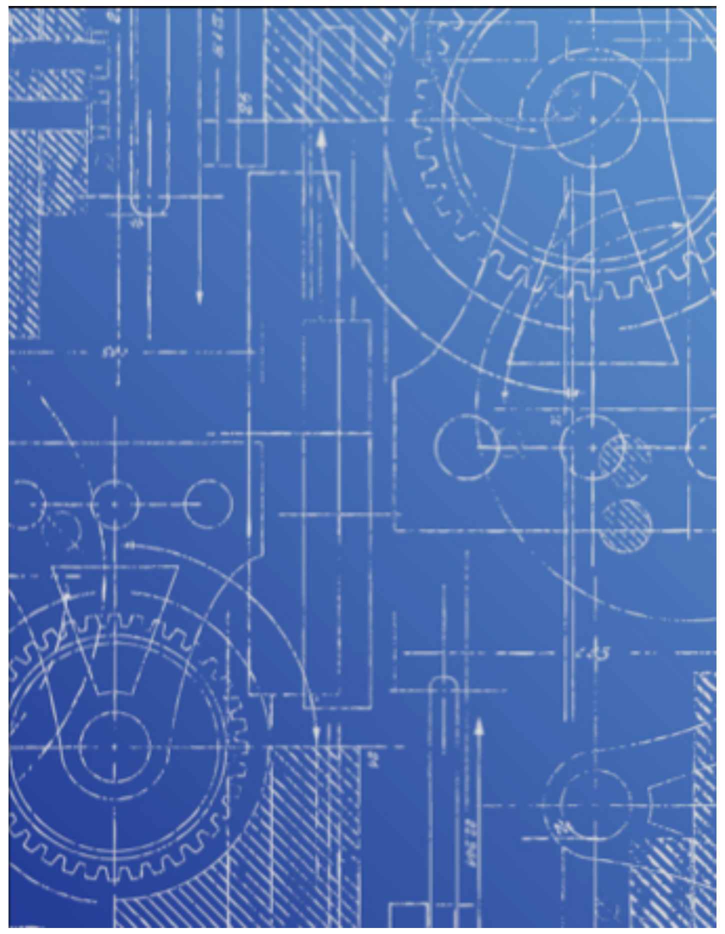
Abstract Interpreter

Concrete Interpreter

Abstraction Specification



+



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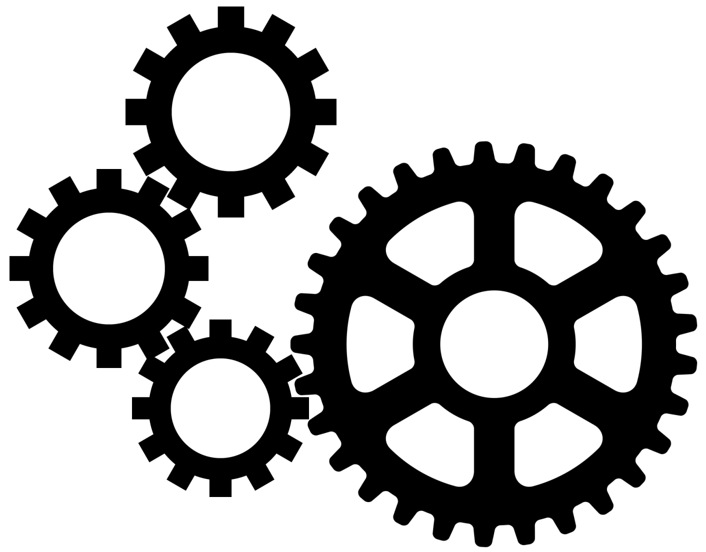
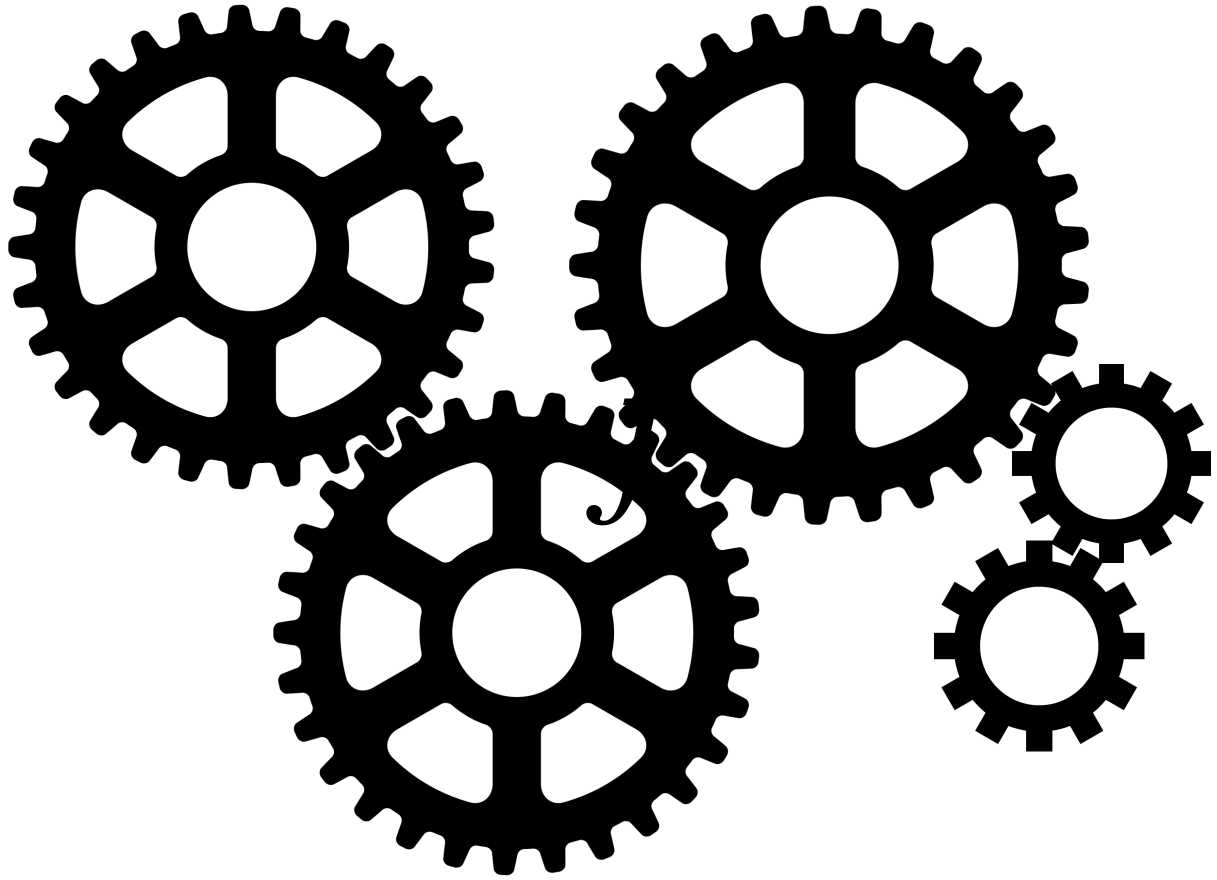


Abstract Interpreter

Concrete Interpreter

Abstraction Specification



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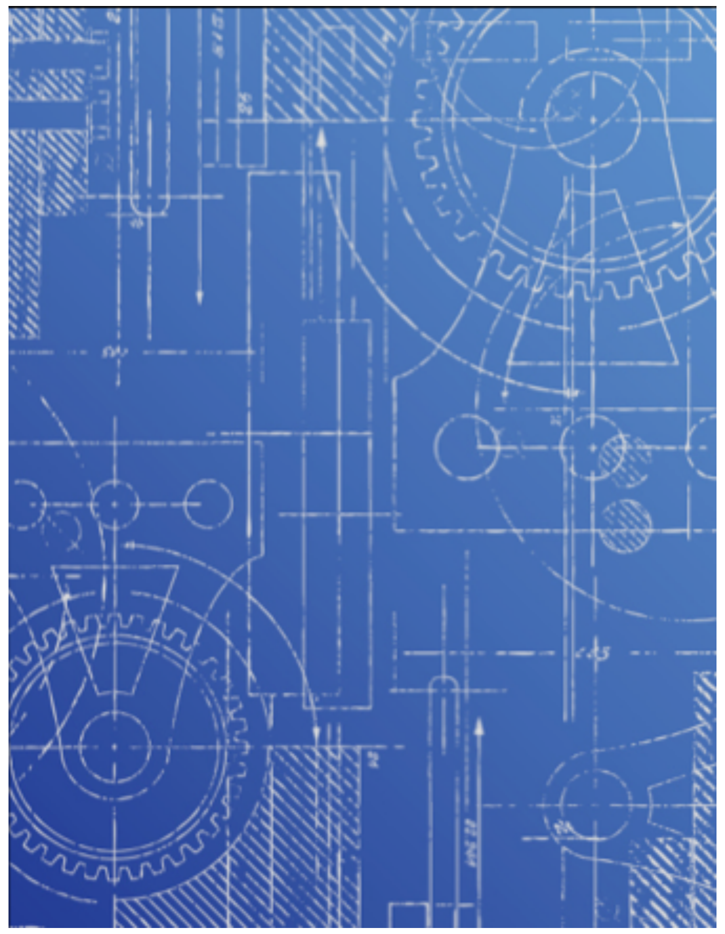

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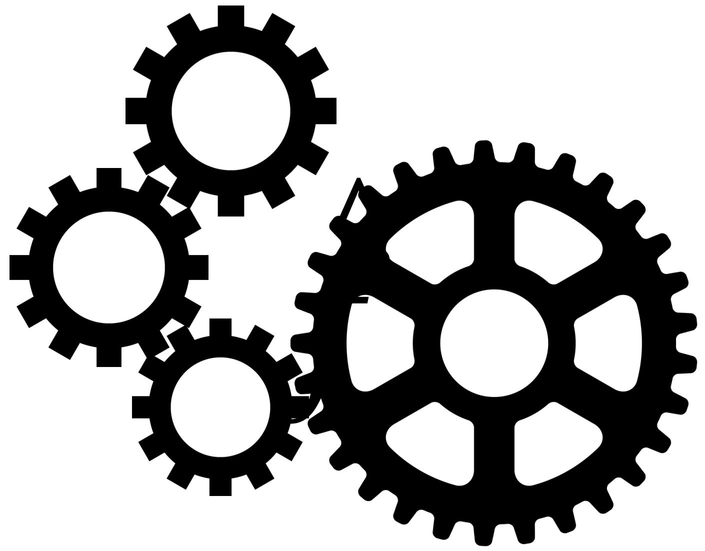


Abstract Interpreter

Concrete Interpreter **Abstraction Specification**

$$f \quad + \quad (\alpha, \gamma)$$

$$= \quad \hat{f}$$

Abstract Interpreter

The calculational approach to Abstract Interpretation

$$\hat{f} = \alpha \circ f \circ \gamma$$

Cousot, Cousot (1976,1977,1979)

```
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```

```
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```

$$\{\textbf{Odd}\} \;\hat{+}\; \{\textbf{Odd}\}$$

```
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```

$$\begin{tikzcd}
\{\textbf{Odd}\} \mathbin{\hat{+}} \{\textbf{Odd}\} \arrow[d, dashed, "\gamma"'] \\
\{\ldots,-3,-1,1,3,\ldots\} + \{\ldots,-3,-1,1,3,\ldots\}
\end{tikzcd}$$

```
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```

$$\begin{tikzcd}
\{\textbf{Odd}\} \mathbin{\hat{+}} \{\textbf{Odd}\} \arrow[d, dashed, "\gamma"'] \\
\{\ldots,-3,-1,1,3,\ldots\} + \{\ldots,-3,-1,1,3,\ldots\} \quad = \quad \{\ldots,-6,-4,-2,0,2,4,6,\ldots\}
\end{tikzcd}$$

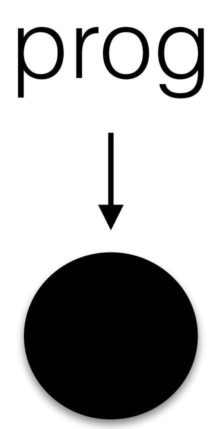
```
public static int nextOdd(int x) {
    if (isEven(x))
        return x+1;
    else return x+2;
}
```

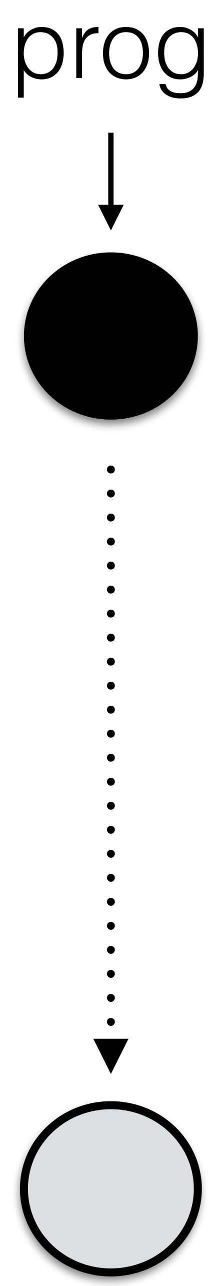
$$\begin{tikzcd}
\{\mathbf{Odd}\} \,\hat{+}\, \{\mathbf{Odd}\} \arrow[d, dashed, "\gamma"'] & {} \\
\{\ldots,\mathbf{-3,-1,1,3,\ldots}\} + \{\mathbf{\ldots,-3,-1,1,3,\ldots}\} \quad = & \{\mathbf{\ldots,-6,-4,-2,0,2,4,6,\ldots}\} \arrow[u, dashed, "\alpha"']
\end{tikzcd}$$

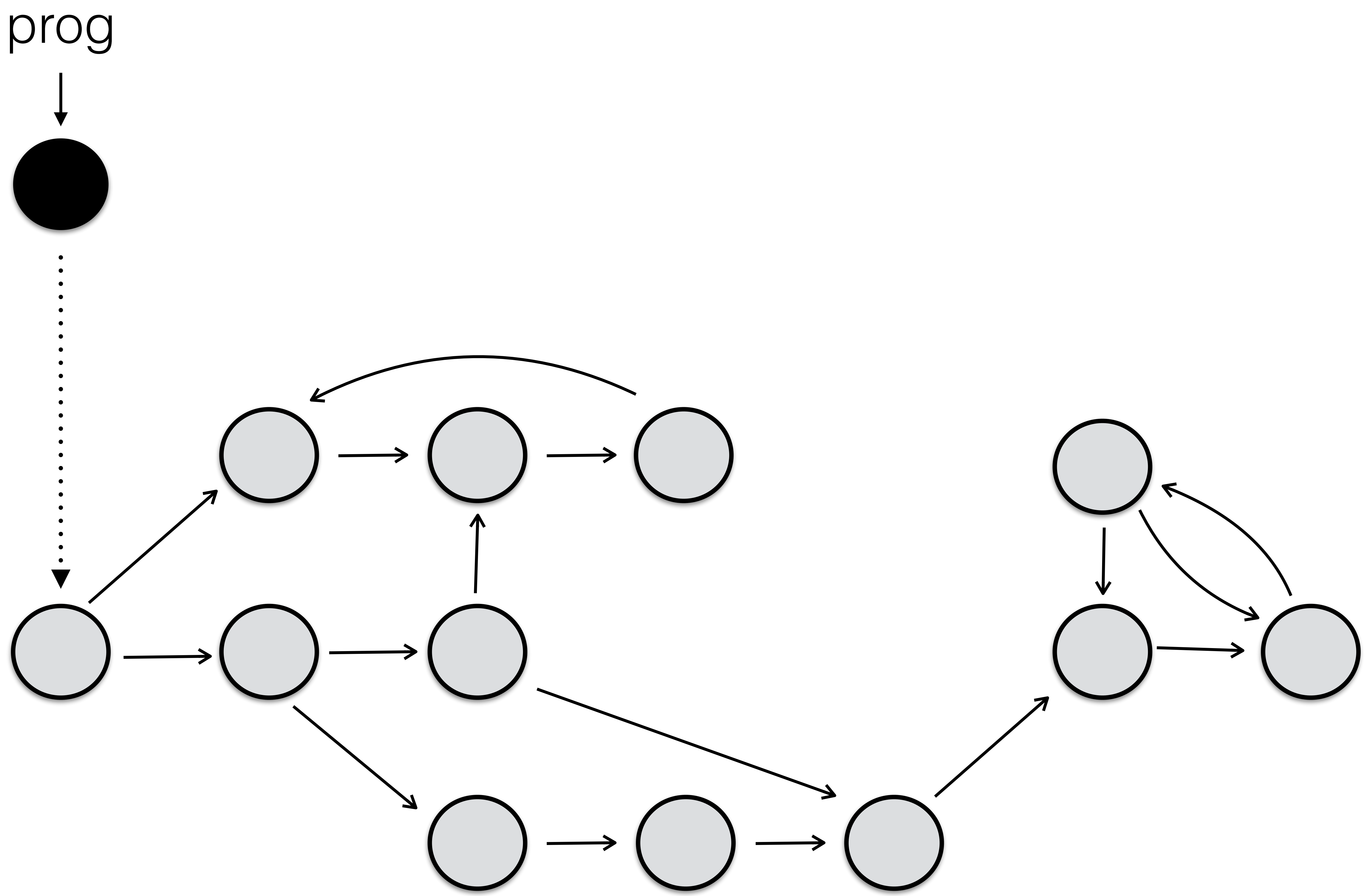
$$(\hat{+}) = \alpha \circ (+) \circ \gamma$$

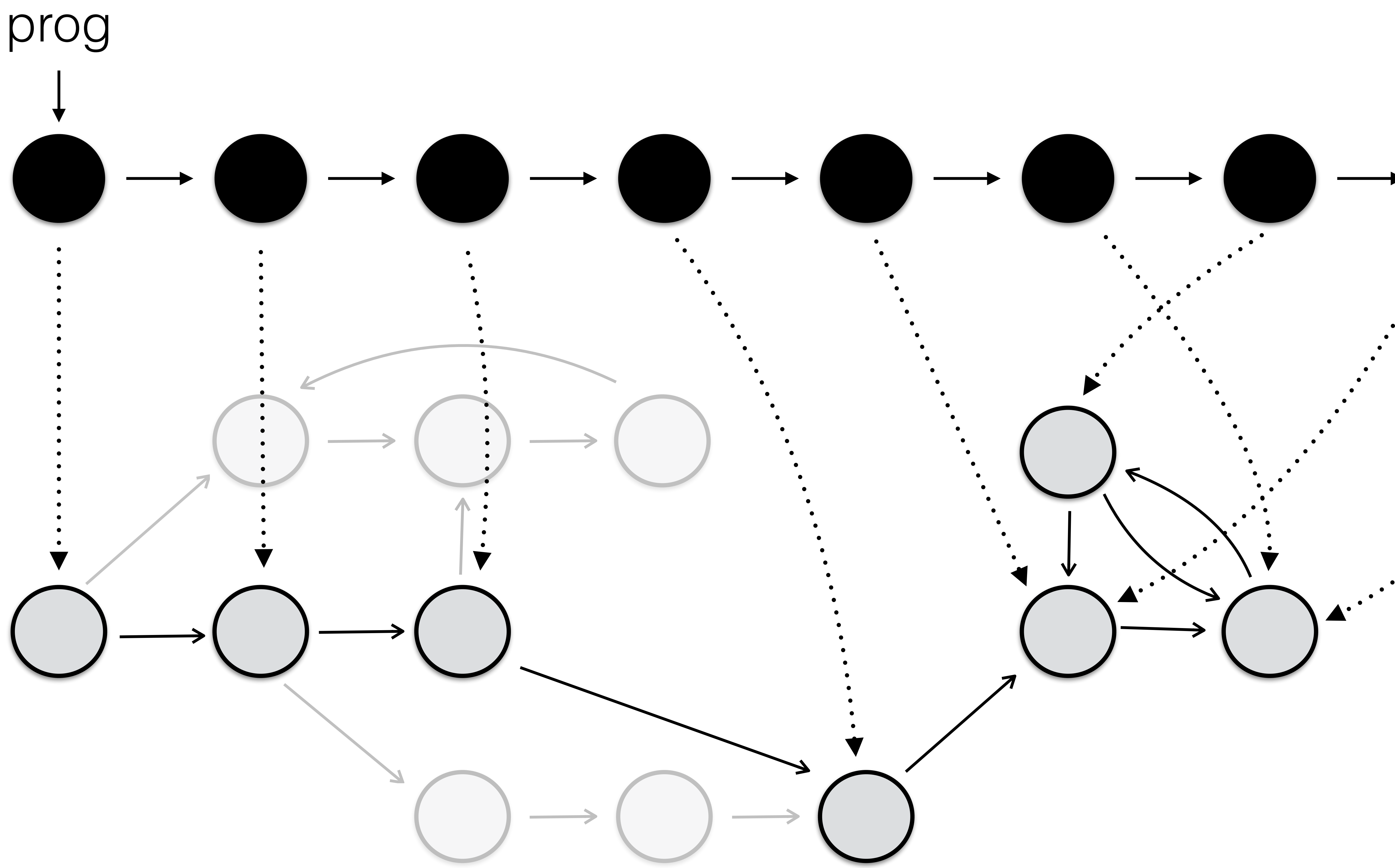
Calculated abstract implementation

$$\begin{tikzcd}
\{\textbf{Odd}\} \;\hat{+}\; \{\textbf{Odd}\} \arrow[d, dashed, "\gamma"'] & = & \{\textbf{Even}\} \\
\{\ldots,\textbf{-3,-1,1,3,}\ldots\} + \{\ldots,\textbf{-3,-1,1,3,}\ldots\} & = & \{\ldots,\textbf{-6,-4,-2,0,2,4,6,}\ldots\} \arrow[u, dashed, "\alpha"']
\end{tikzcd}$$


prog

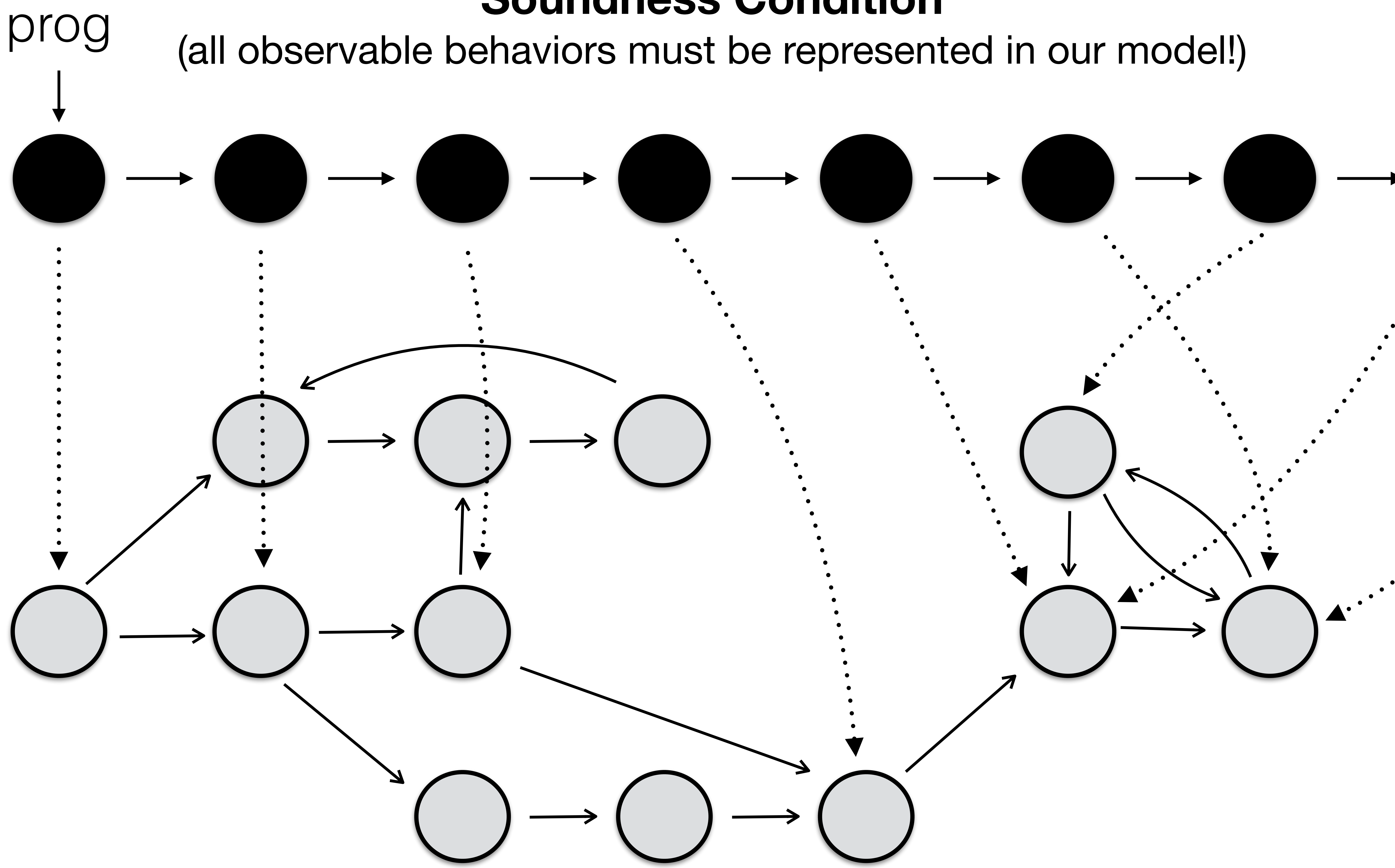

prog


prog


prog

Soundness Condition

(all observable behaviors must be represented in our model!)



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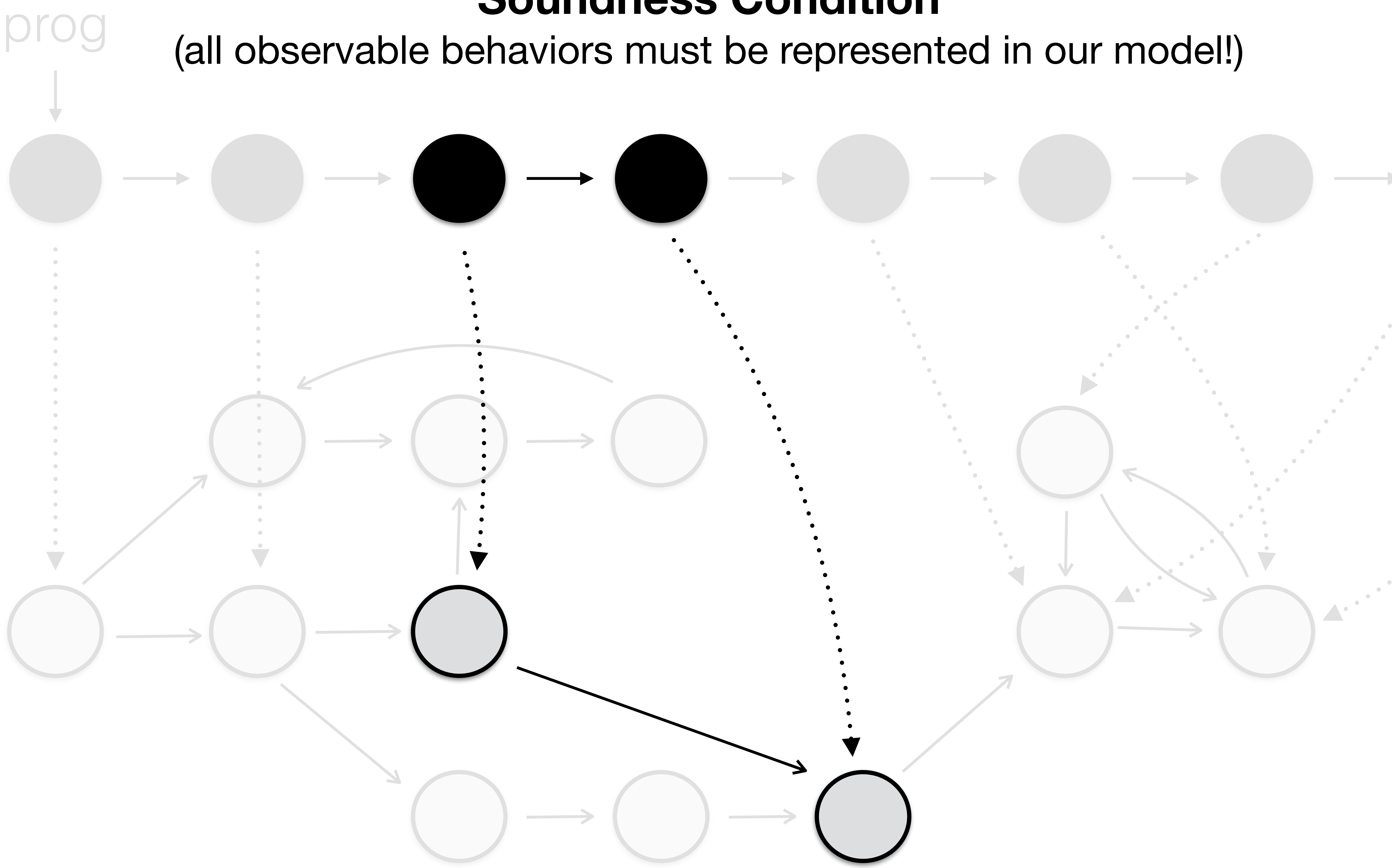

Abstract Interpretation

+

Symbolic Execution

```
    }

    return e;
}


void insert(const T& ele, s64 index = 0)
{
     // Precondition:
     assert(length >= index);

     // Possible reallocation, shift-back

     // Placement-new a T at index
     new (&buff[index]) T(ele);

     // Postcondition:
     assert(length <= buff_length);
}
```

```
    }

    return e;
}


void insert(const T& ele, s64 index = 0)
{
    // Precondition:
    if (!(length >= index))
        err(“Assert failed.”);

    // Possible reallocation, shift-back

    // Placement-new a T at index
    new (&buff[index]) T(ele);

    // Postcondition:
    if (!(length <= buff_length))
        err(“Assert failed.”);
}
```

```
    }

    return e;
}
```

$\textbf{this} = \alpha \quad \textbf{ele} = \beta \quad \textbf{index} = \gamma$

```
void insert(const T& ele, s64 index = 0)
{
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    // Postcondition:
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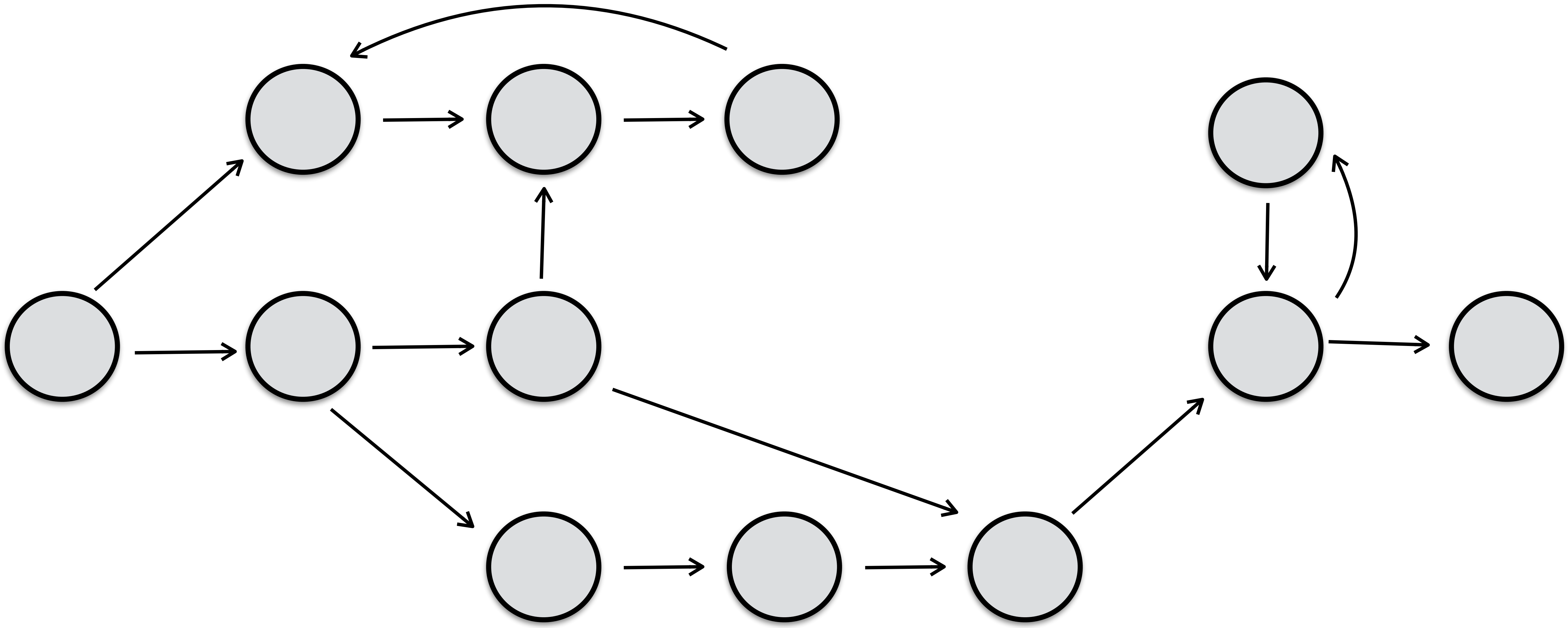
        err("Assert failed.");
}
```

$\alpha.\textbf{length} < \gamma$

$\alpha.\textbf{length} >= \gamma$

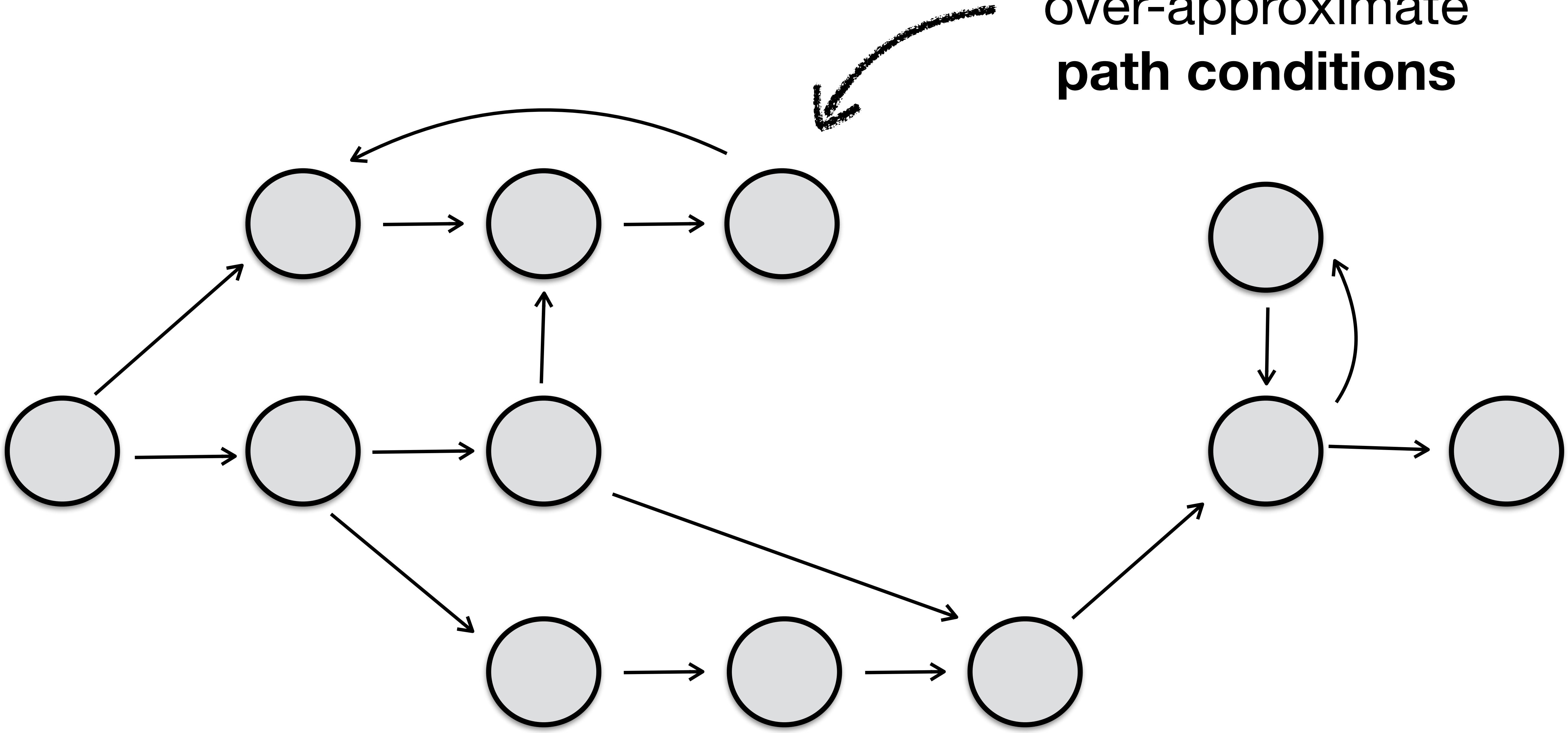
Abstract Symbolic Execution



"Soft Contract Verification for Higher-order Stateful Programs".
Nguyễn, Gilray, Tobin-Hochstadt, Van Horn. 2018.

Abstract Symbolic Execution

Instrument states with over-approximate **path conditions**



“Soft Contract Verification for Higher-order Stateful Programs”.
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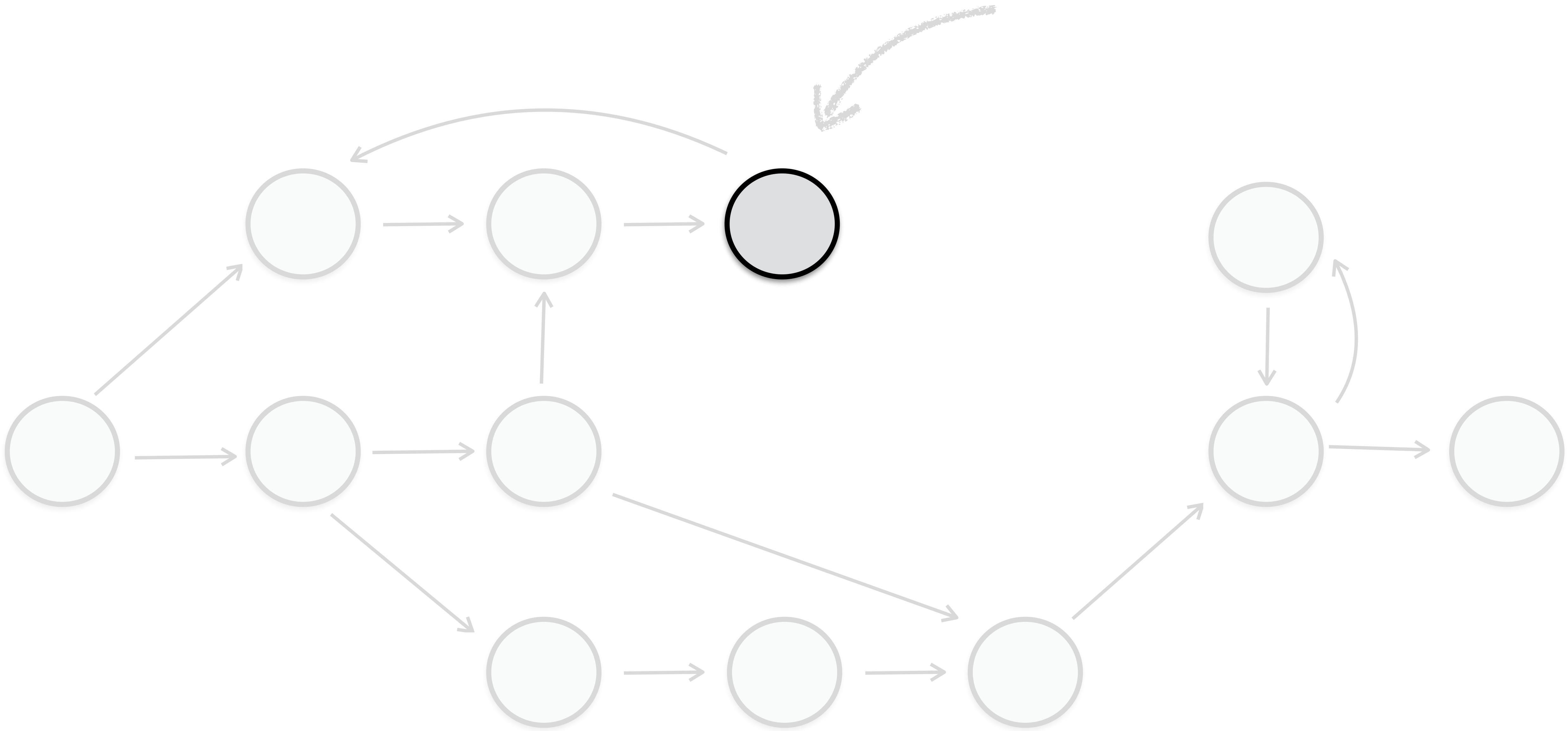
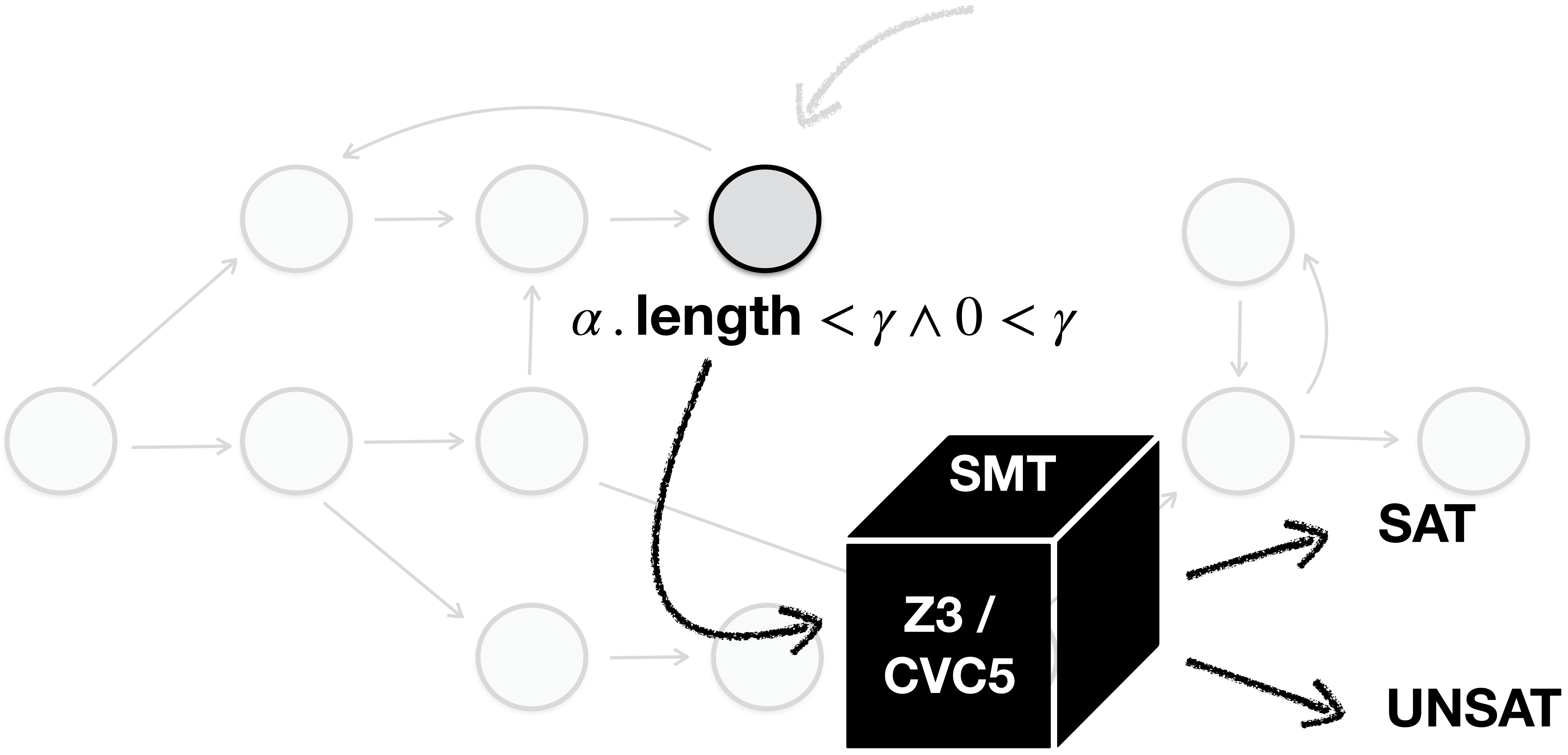
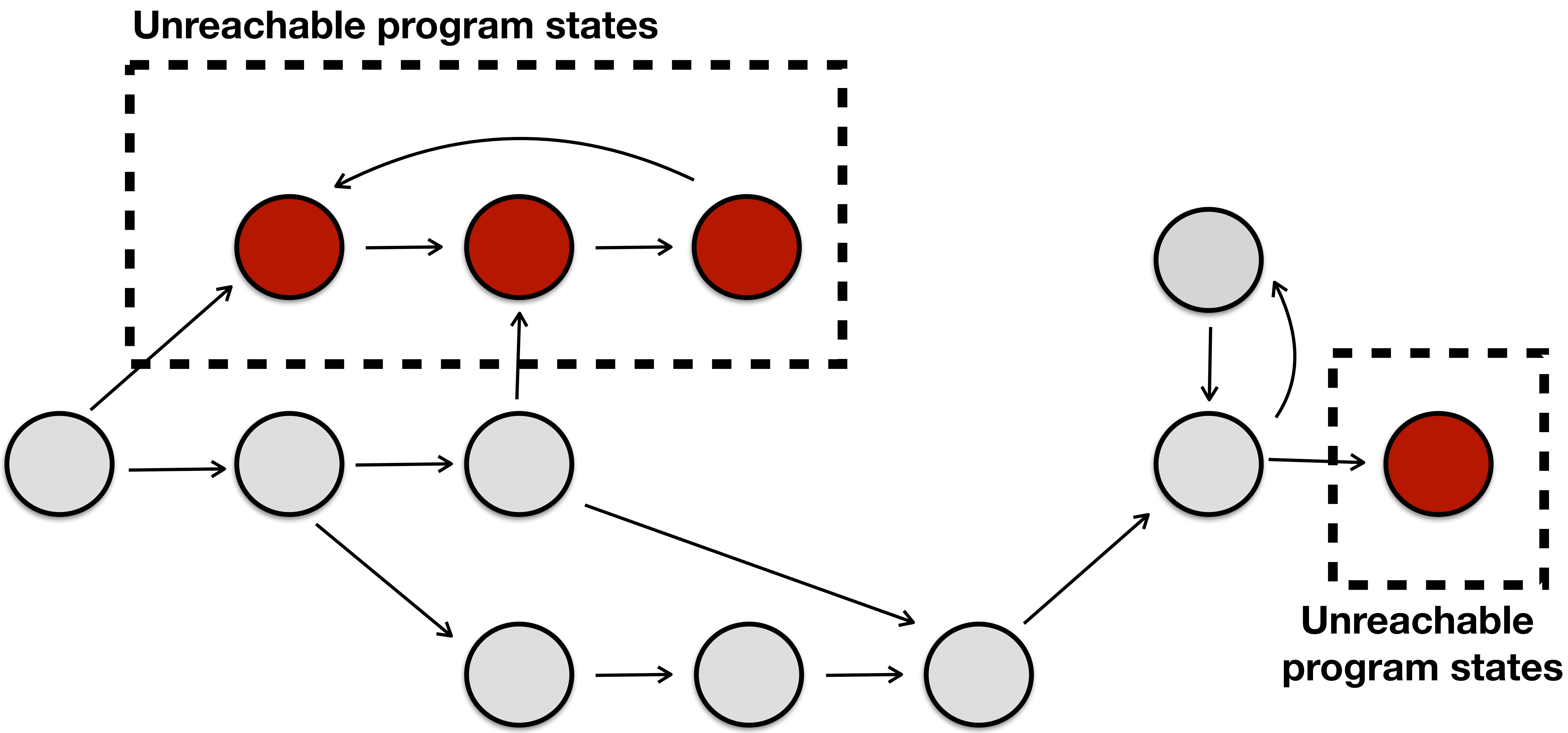



α.length $< \gamma \land 0 < \gamma$
SMT
Z3 / CVC5
SAT
UNSAT

Abstract Symbolic Execution



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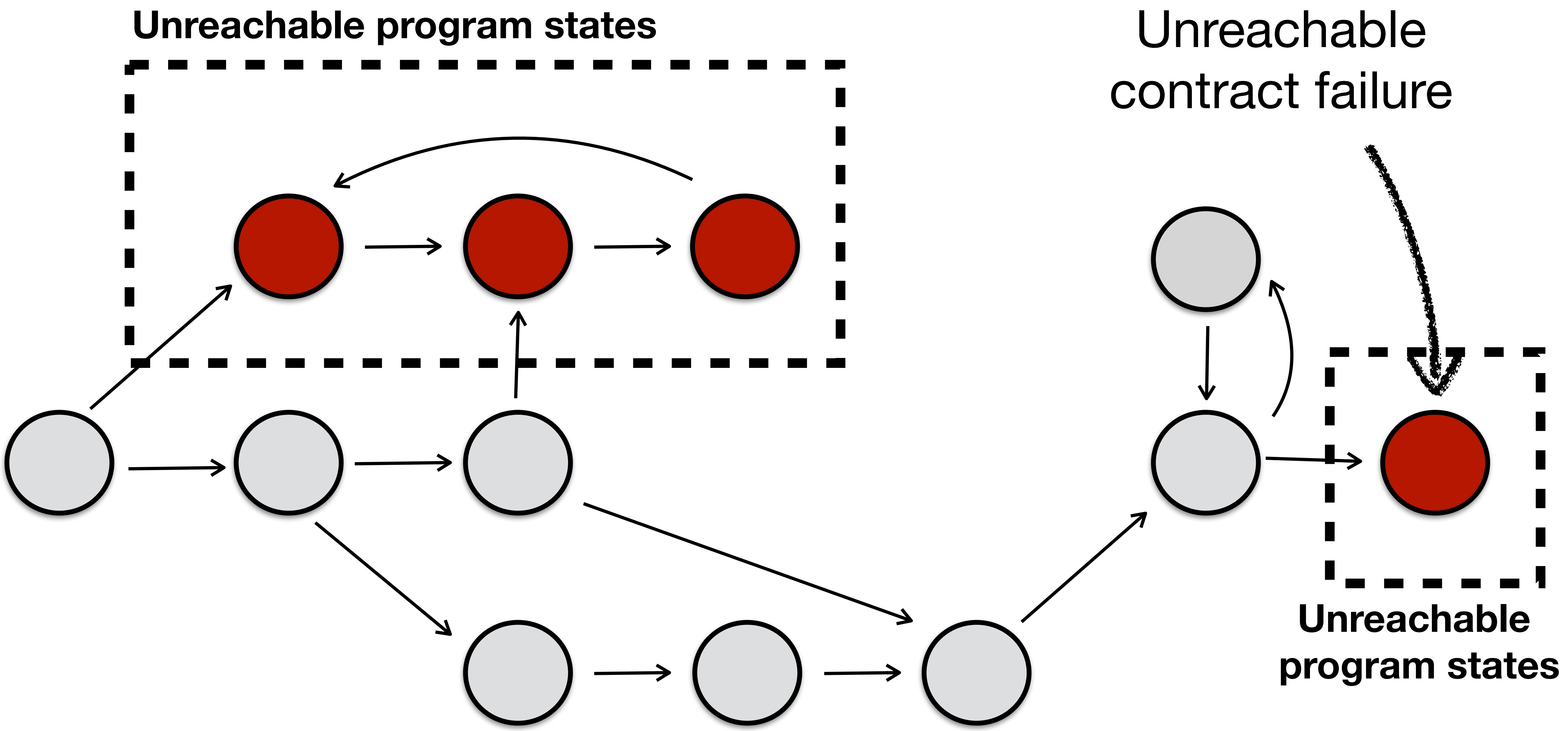
Abstract Symbolic Execution


Unreachable program states
Unreachable contract failure
Unreachable program states

“Soft Contract Verification for Higher-order Stateful Programs”.
Nguyễn, Gilray, Tobin-Hochstadt, Van Horn. 2018.

```
// [number] -> [string]
function array_numtostr(arr) {
    assert(arr instanceof Array
        && arr.reduce((a,n)=>(typeof n)
=="number" && a, true));

    var str_arr = [];
    for (var i = 0; i < arr.length; ++i)
        str_arr.push(arr[i]+"");

    assert(str_arr instanceof Array
        && str_arr.reduce((a,s)=>(typeof s)
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    return str_arr
}
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- This gives a precise run-time bound, ***defining correct behavior***.

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Thanks

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