Autumn 2017

(Advanced) topics in Programming Languages

Instructor: Mooly Sagiv

Dan David 203

http://www.cs.tau.ac.il/~msagiv/courses/apl17.html

Prerequisites

- Compilation course or
- Programming Languages

Course Grade

- 10% Class notes
- 35% (Mainly Theoretical) Assignments
- 55% Home or (easier) class exam

Class Notes

- Prepared by two/three students
- First draft completed within one week
- Consumes a lot of time
- Use LaTeX template provided in the homepage
- Read supplementary material
- Correct course notes
  - Bonus for interesting corrections
- Add many more examples and elaborations

1. Performance
2. Security
3. Productivity

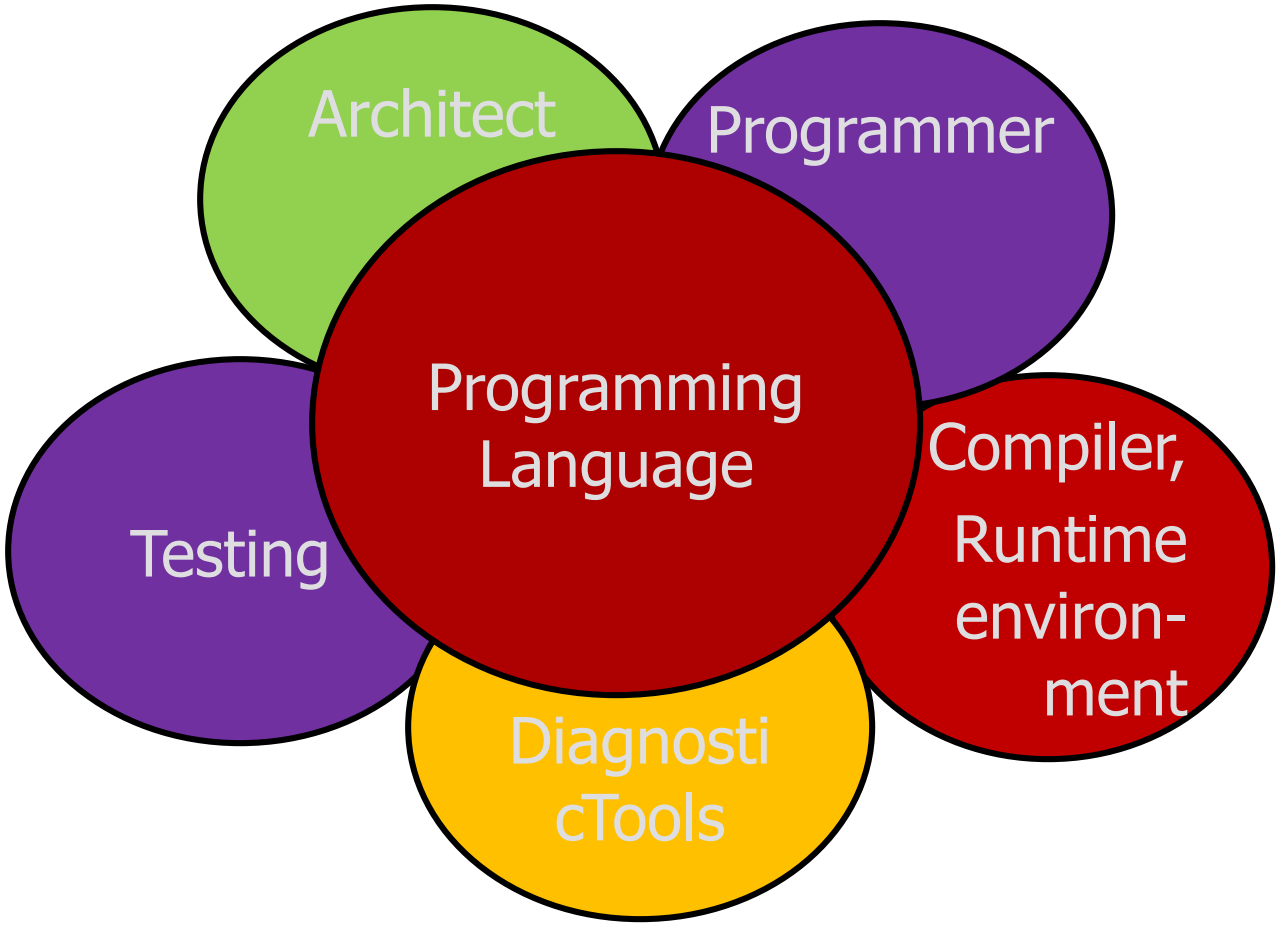
New PL in Industry

PL	Company	Predecessor	Domain	Concepts
Go	Google	C	Systems	Channels Type Inference ML modules GC
Dart	Google	Javascript	Web	Types
Rust		C++	System Browser	Type Inference Ownership Linear Types
Hack	facebook	PHP	Social Networks	Gradual Types

Course Themes

- Programming Language Concepts
  - A language is a “conceptual universe” (Perlis)
    - Framework for problem-solving
    - Useful concepts and programming methods
  - Understand the languages you use, by comparison
  - Appreciate history, diversity of ideas in programming
  - Be prepared for new programming methods, paradigms, tools
- Critical thought
  - Identify properties of *language*, not syntax or sales pitch
- Language *and* implementation
  - Every convenience has its cost
    - Recognize the cost of presenting an abstract view of machine
    - Understand trade-offs in programming language design

Language goals and trade-offs



Instructor’s Background

- First programming language Pascal
- Soon switched to C (unix)
  - Efficient low level programming was the key
  - Small programs did amazing things
- Led an industrial project was written in common lisp
  - Semi-automatically port low level OS code between 16 and 32 bit architectures
- The programming setting has dramatically changed:
  - Object oriented
  - Garbage collection
  - Huge programs
  - Performance depends on many issues
  - Productivity is sometimes more importance than performance
  - Software reuse is a key

Other Lessons Learned

- Futuristic ideas may be useful problem-solving methods now, and may be part of languages you use in the future
  - Examples
    - Recursion
    - Object orientation
    - Garbage collection
    - High level concurrency support
    - Higher order functions
    - Pattern matching

More examples of practical use of futuristic ideas

- Function passing: pass functions in C by building your own closures, as in STL “function objects”
- Blocks are a nonstandard extension added by Apple to C that uses a lambda expression like syntax to create closures
- Continuations: used in web languages for workflow processing
- Monads: programming technique from functional programming
- Concurrency: atomicity instead of locking
- Decorators in Python to dynamically change the behavior of a function

What's new in programming languages

- Commercial trend over past 5+ years
  - Increasing use of type-safe languages: Java, C#, …
  - Scripting languages, other languages for web applications
- Teaching trends
  - Java replaced C as most common intro language
    - Less emphasis on how data, control represented in machine
- Research and development trends
  - Modularity
    - Java, C++: standardization of new module features
  - Program analysis
    - Automated error detection, programming env, compilation
  - Isolation and security
    - Sandboxing, language-based security, …
  - Web 2.0
    - Increasing client-side functionality, mashup isolation problems

What's worth studying?

- Dominant languages and paradigms
  - Leading languages for general systems programming
  - Explosion of programming technologies for the web
- Important implementation ideas
- Performance challenges
  - Concurrency
- Design tradeoffs
- Concepts that research community is exploring for new programming languages and tools
- Formal methods in practice
  - Grammars
  - Semantics
  - Domain theory
  - …

Suggested Reading

- J. Mitchell. Concepts in Programming Languages
- B. Pierce. Types and Programming Languages
- J. Mitchell. Foundations for Programming Languages
- Glynn Winskel. Formal Semantics of Programming Languages
- C. A. R. Hoare. An axiomatic basis for computer programming. *Communications of the ACM*, 12(10):576-580 and 583, October 1969
- Peter J. Landin. The next 700 programming languages
- …

Related Courses

- Compilers
- Programming languages
- Semantics of programming languages
- Program analysis

Syntax vs. Semantics

- The pattern of formation of sentences or phrases in a language
- Examples
  - Regular expressions
  - Context free grammars

- The study or science of meaning in language
- Examples
  - Interpreter
  - Compiler
  - Better mechanisms will be given in the course

Syntax vs. Semantics Propositional Logic

- Syntax: Boolean formulas over variables
  - <Formula> ::= Variable | <Formula> ‘|’ <Formula> | <Formula> ‘&’ <Formula> | ‘!’ <Formula> | ‘(‘ <Formula> ‘)’
- Semantics:

Who need formal semantics for PL?

- Language designers
- Compiler designers
- Programmers

Example C++

- Designed with a source to source compiler to C
- Many issues
  - Especially later

Type Safety

- A programming language is type safe if every well typed program has no undefined semantics
- No runtime surprise
- Is C type safe?
- How about Java?

Breaking Safety in C

```
void foo(s) {
   char c[100];
   strcpy(c, s);
        }
```

A Pathological C Program

```
a =  malloc(…) ;
b = a;
free (a);
c = malloc (…);
if  (b == c)  printf("unexpected equality");
```

Another Pathological C Program

```
union { int x;
        int *p;
      } mixed;
mixed.x = 1700 ;
free(mixed.p);
```

Alternative Formal Semantics

- Operational Semantics
  - The meaning of the program is described "operationally"
  - Natural Operational Semantics
  - Structural Operational Semantics
- Denotational Semantics
  - The meaning of the program is an input/output relation
  - Mathematically challenging but complicated
- Axiomatic Semantics
  - The meaning of the program are observed properties

Alternate Semantics

- What is the meaning of a program?
- “int f(int x) { int y=x; return y + 1 ;}“
- Operational
- Denotational
- Axiomatic

Semantics of Arithmetic Expressions

- Syntax
- Semantics

States

- Mapping of variables into values
- $Var \rightarrow Z$
  - Can be partial
- Examples $[x \mapsto 1, y \mapsto 7]$

Example State Manipulations

- $[x \mapsto 1, y \mapsto 7]\ y =$
- $[x \mapsto 1, y \mapsto 7]\ t =$

Semantics of arithmetic expressions

- Assume that arithmetic expressions are side-effect free
- $A[\![Aexp]\!] : State \rightarrow Z$
- Defined by structural induction on the syntax tree
  - $A[\![n]\!] s = n$
  - $A[\![x]\!] s = s\ x$
  - $A[\![e_1 + e_2]\!] s = A[\![e_1]\!] s + A[\![e_2]\!] s$
  - $A[\![e_1 * e_2]\!] s = A[\![e_1]\!] s * A[\![e_2]\!] s$
  - $A[\![(e_1)]\!] s = A[\![e_1]\!] s$ --- not needed
  - $A[\![- e_1]\!] s = -A[\![e_1]\!] s$

Properties of arithmetic expressions

- The semantics is compositional
  - $A[\![e_1 \text{ op } e_2]\!] = [\![\text{op}]\!] (A[\![e_1]\!], A[\![e_2]\!])$
  - Properties can be proved by structural induction
- We say that e_1 is semantically equivalent to e_2 ($e_1 \approx e_2$) when $A[\![e_1]\!] = A[\![e_2]\!]$

Commutativity of expressions

- Theorem: for every expressions e_1, e_2: $e_1 + e_2 \approx e_2 + e_1$
- Proof:

$$A[\![e_1 + e_2]\!]s = A[\![e_1]\!]s + A[\![e_2]\!]s = A[\![e_2]\!]s + A[\![e_1]\!]s = A[\![e_2 + e_1]\!]s$$

Program Analysis

- Automatically infer properties of programs
- Identify potential bugs
- Prove the absence of errors

- A sailor on the U.S.S. Yorktown entered a 0 into a data field in a kitchen-inventory program
- The 0-input caused an overflow, which crashed all LAN consoles and miniature remote terminal units
- The Yorktown was dead in the water for about two hours and 45 minutes

Numeric static analysis can detect these errors when the ship is built!

- A sailor on the U.S.S. Yorktown entered a 0 into a data field in a kitchen-inventory program
- The 0-input caused an overflow, which crashed all LAN consoles and miniature remote terminal units
- The Yorktown was dead in the water for about two hours and 45 minutes

```
x = 3;
y = 1/(x-3);
```

need to track values other than 0

```
x = 3;
px = &x;
y = 1/(*px-3);
```

need to track pointers

```
for (x =5; x < y ; x++) {
    y = 1/ z - x
```

Need to reason about loops

Dynamic Allocation (Heap)

```
x = 3;
p = (int*)malloc(sizeof int);
*p = x;
q = p;
y = 1/(*q-3);
```

need to track heap-allocated storage

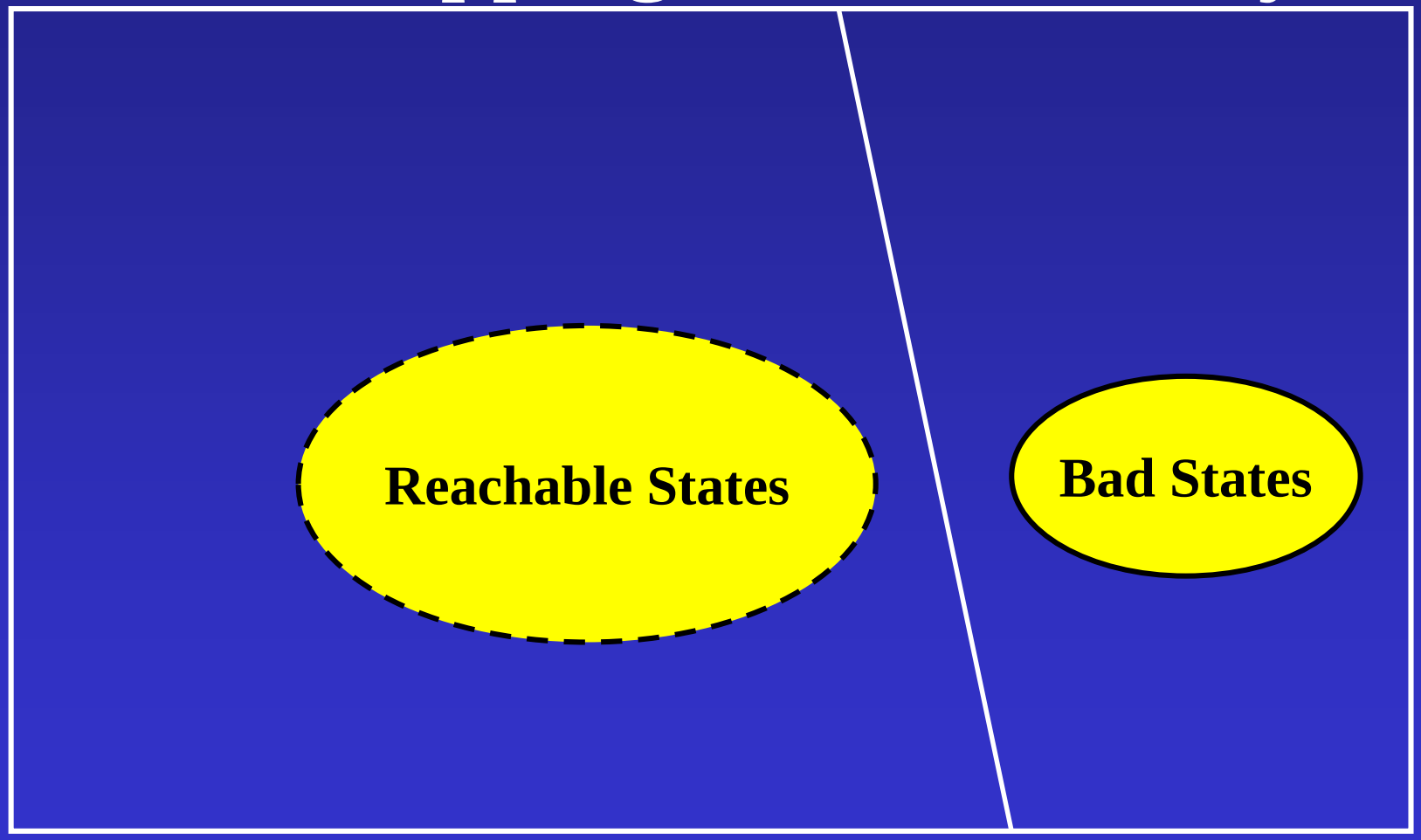
Why is Program Analysis Difficult?

- Undecidability
  - Checking if program point is reachable
    - The Halting Problem
  - Checking interesting program properties
    - Rice Theorem
  - Can the computer really perform inductive reasoning?

Why is Program Analysis Difficult?

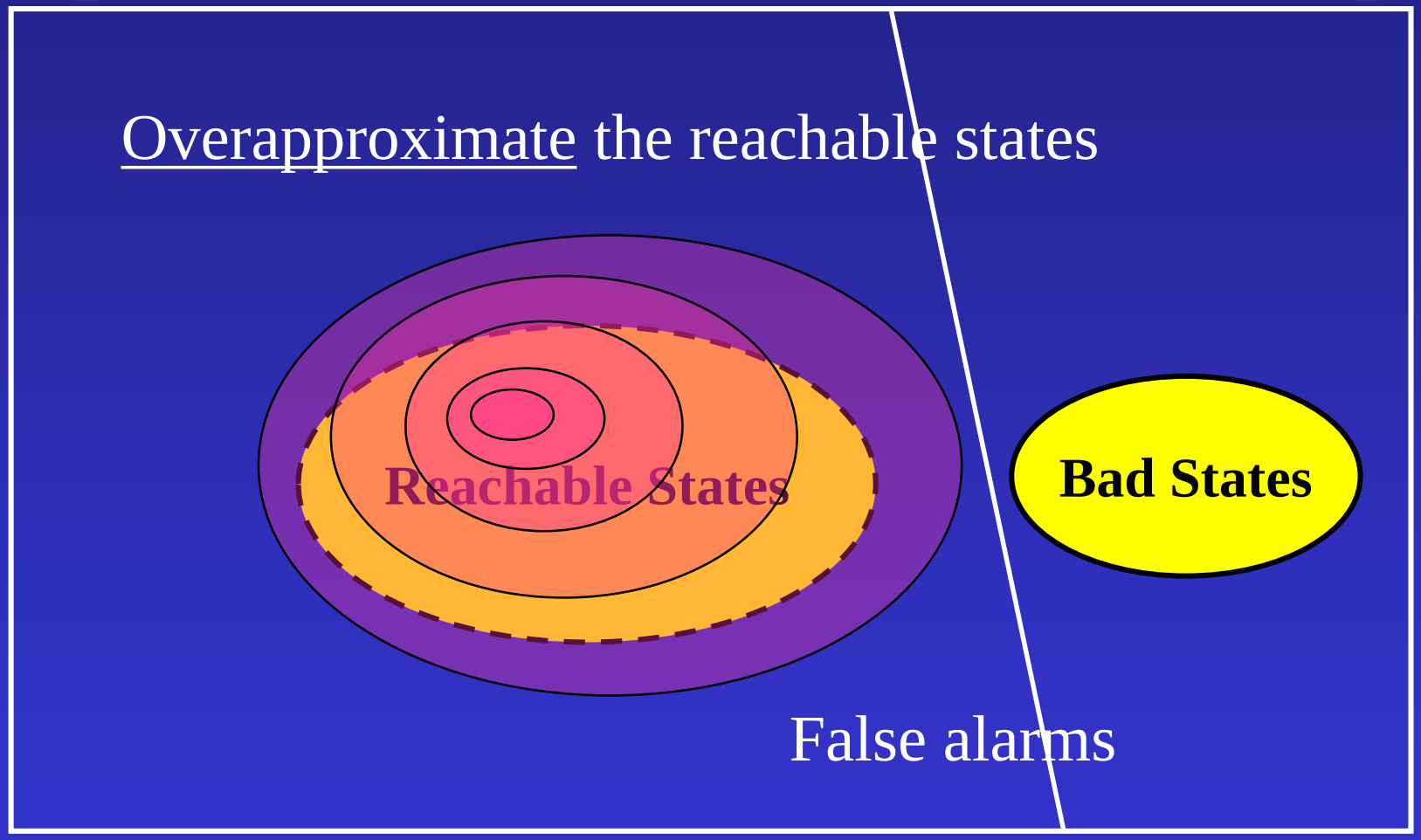
- Complicated programming languages
  - Large/unbounded base types: **`int`**, **`float`**, **`string`**
  - Pointers/aliasing + unbounded #'s of heap-allocated cells
  - User-defined types/classes
  - Loops with unbounded number of iterations
  - Procedure calls/recursion/calls through pointers/dynamic method lookup/overloading
  - Concurrency + unbounded #'s of threads
- Conceptual
  - Which program to analyze?
  - Which properties to check?
- Scalability

Sidestepping Undecidability



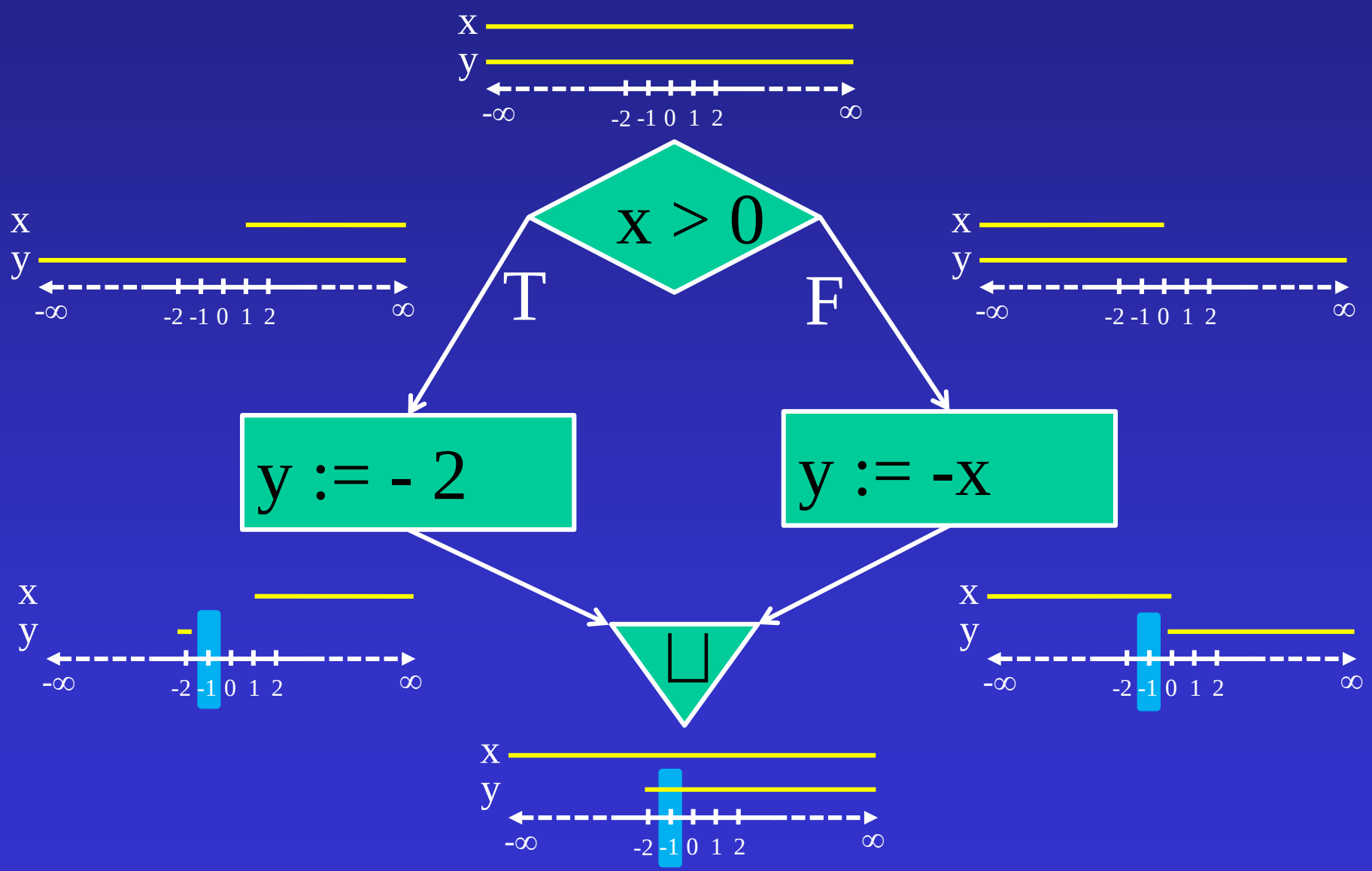
Universe of States

Sidestepping Undecidability [Cousot & Cousot POPL77-79]

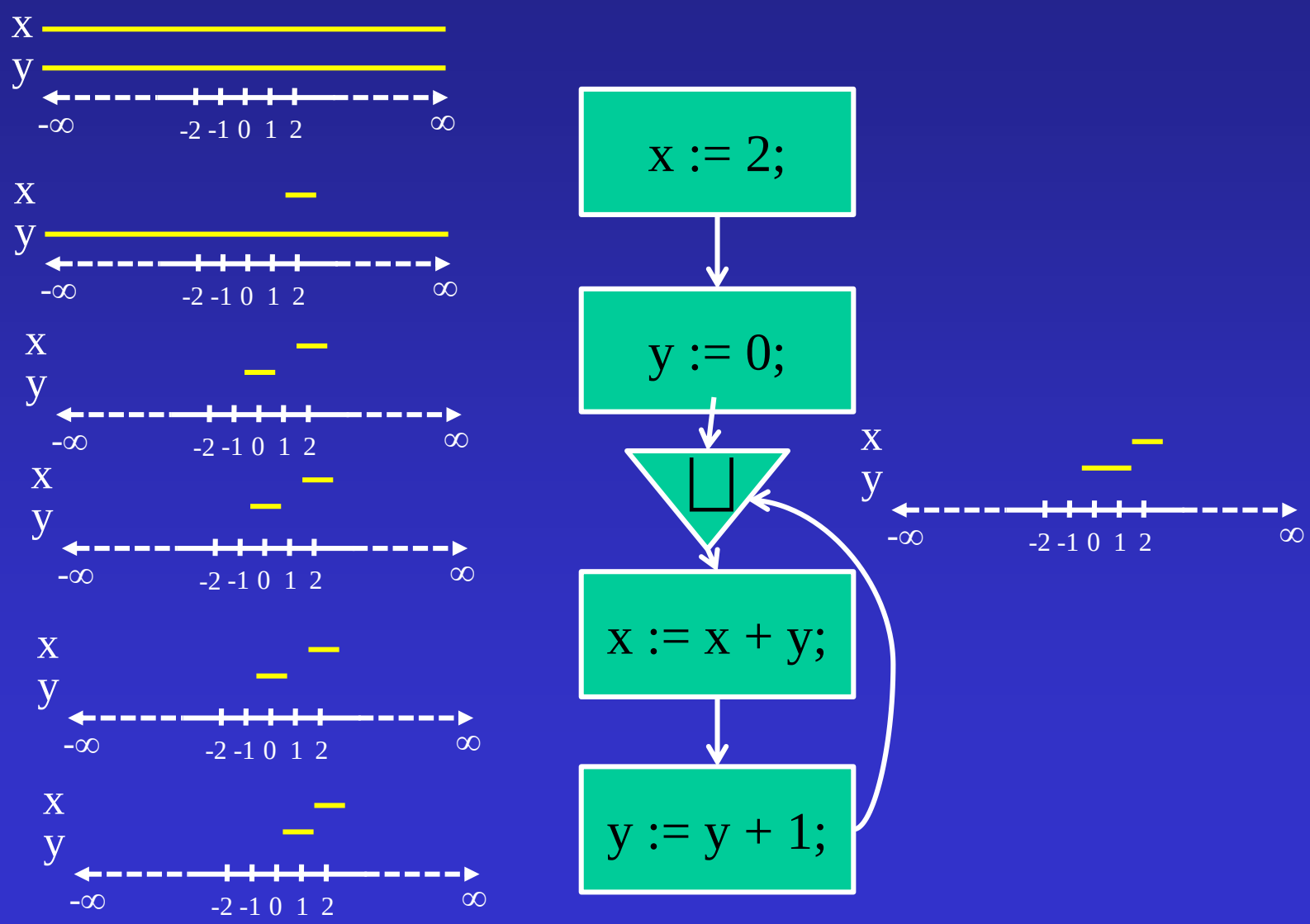


Universe of States

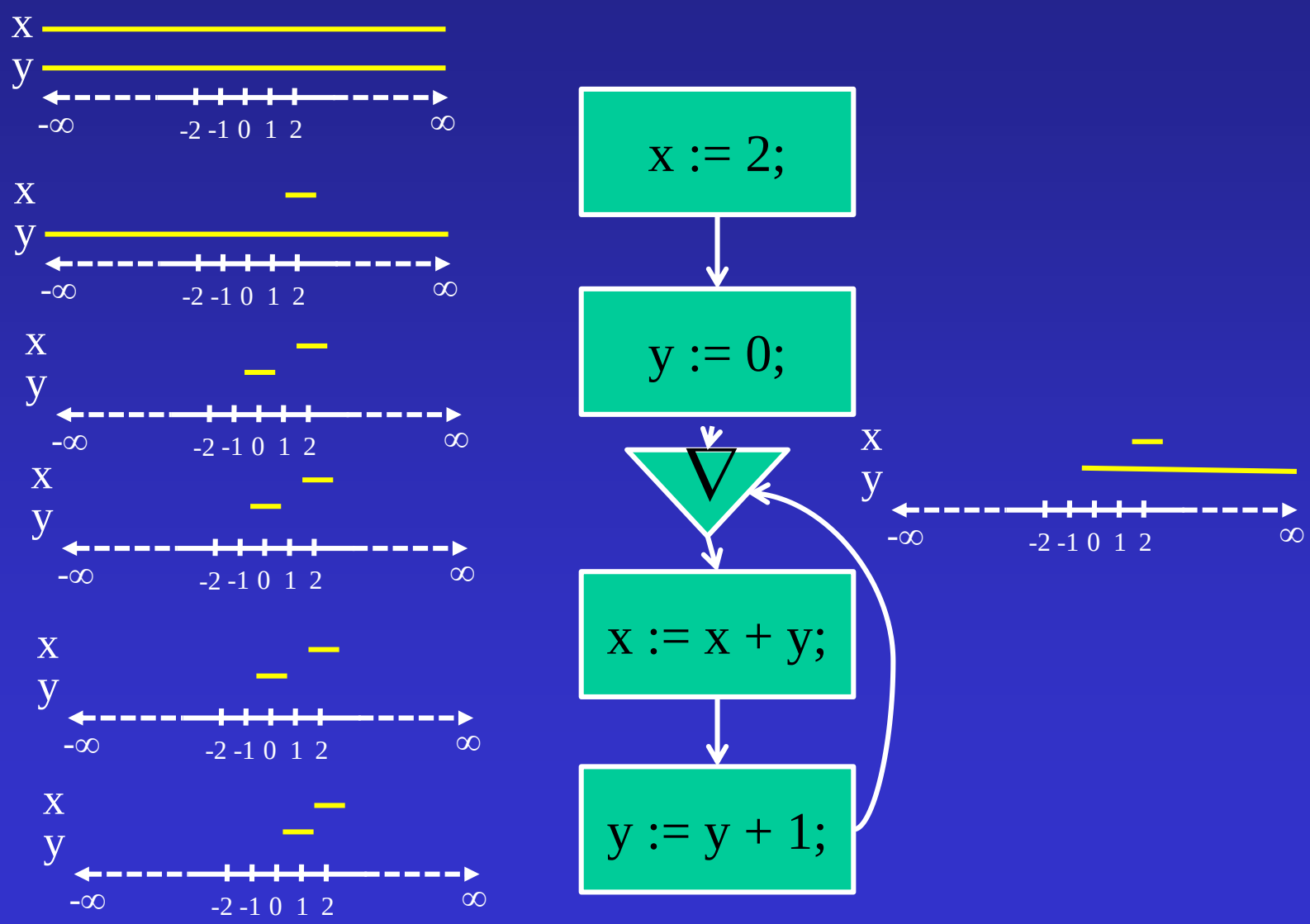
Abstract Interpretation



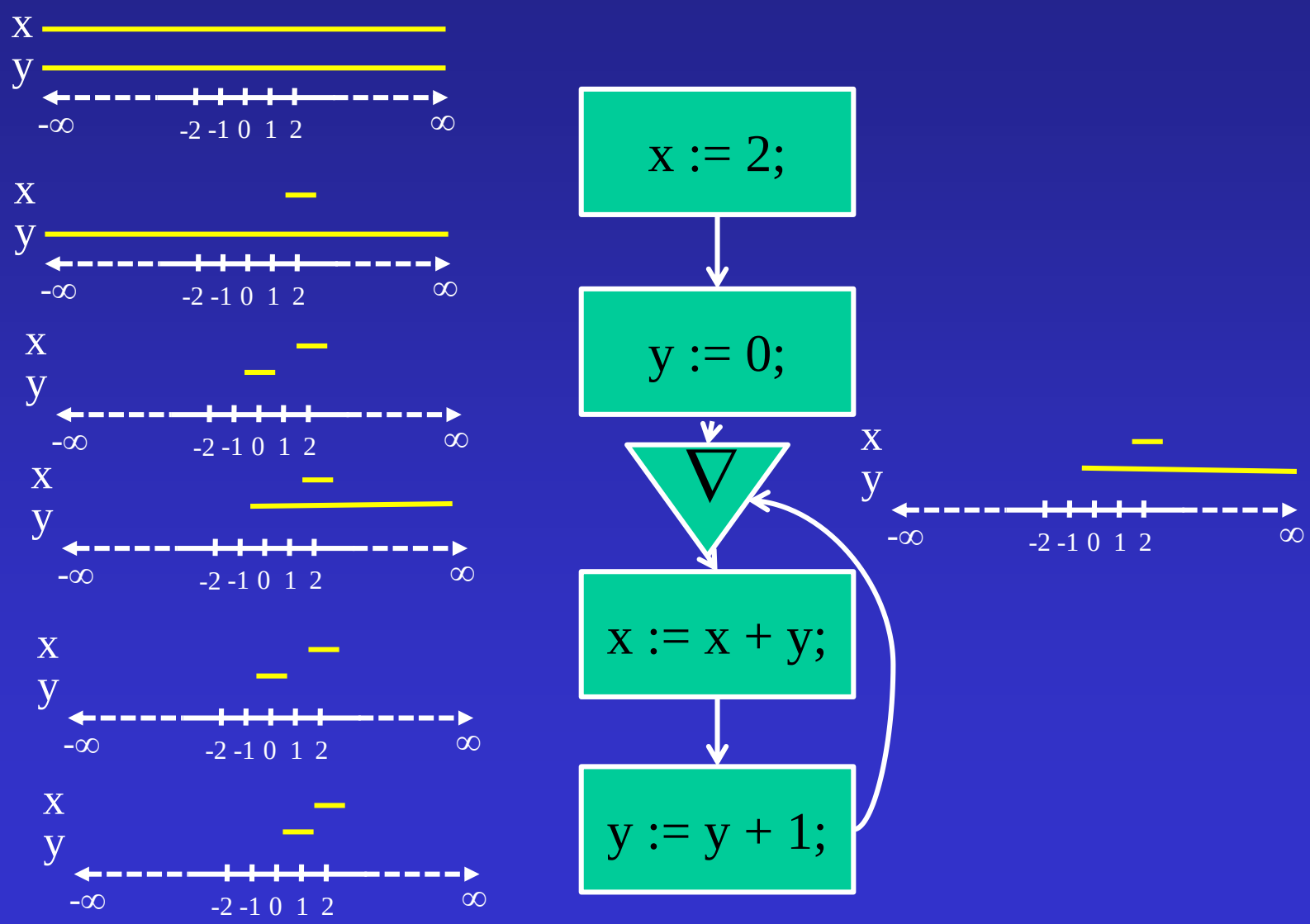
Infer Inductive Invariants via AI



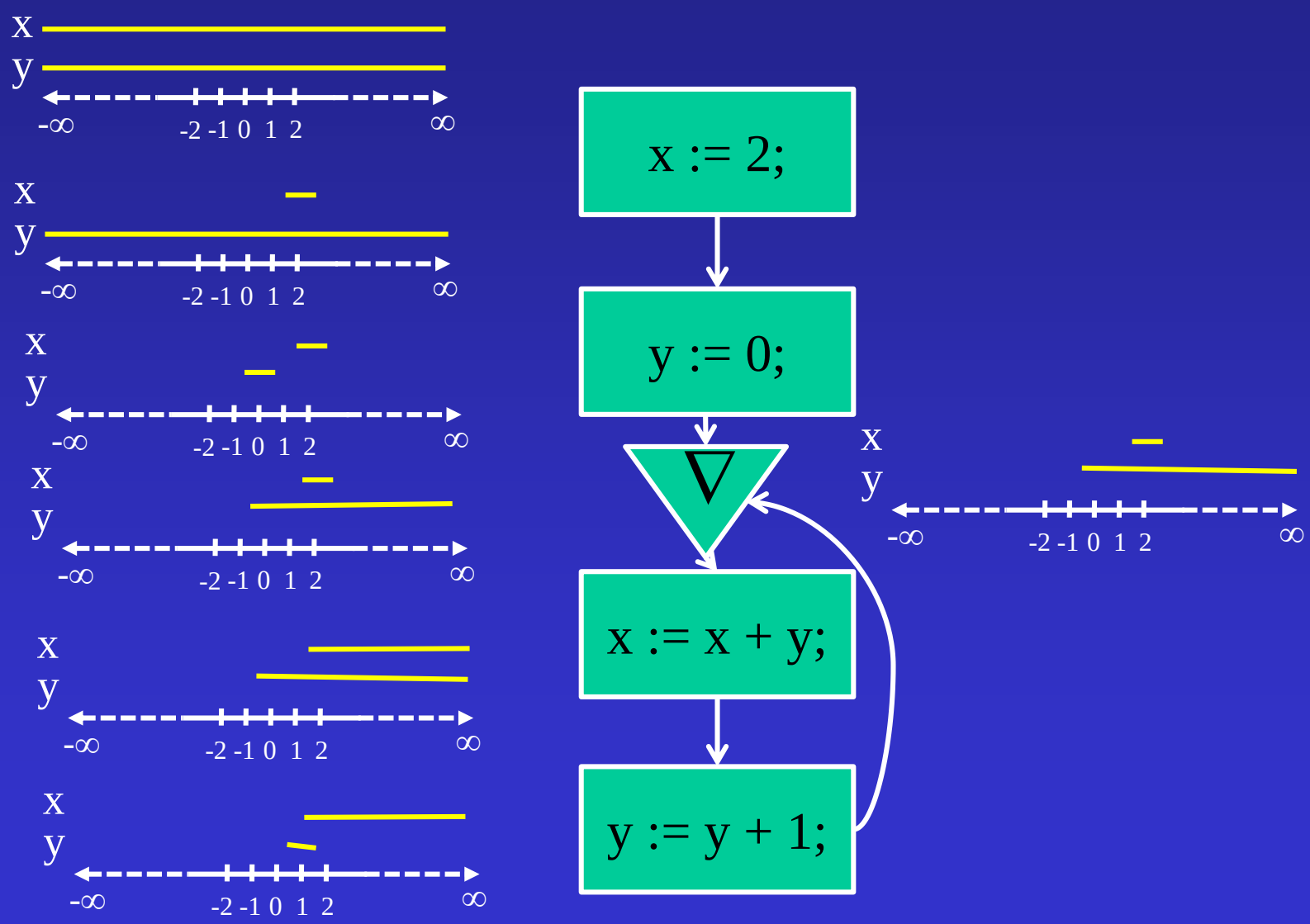
Infer Inductive Invariants via AI



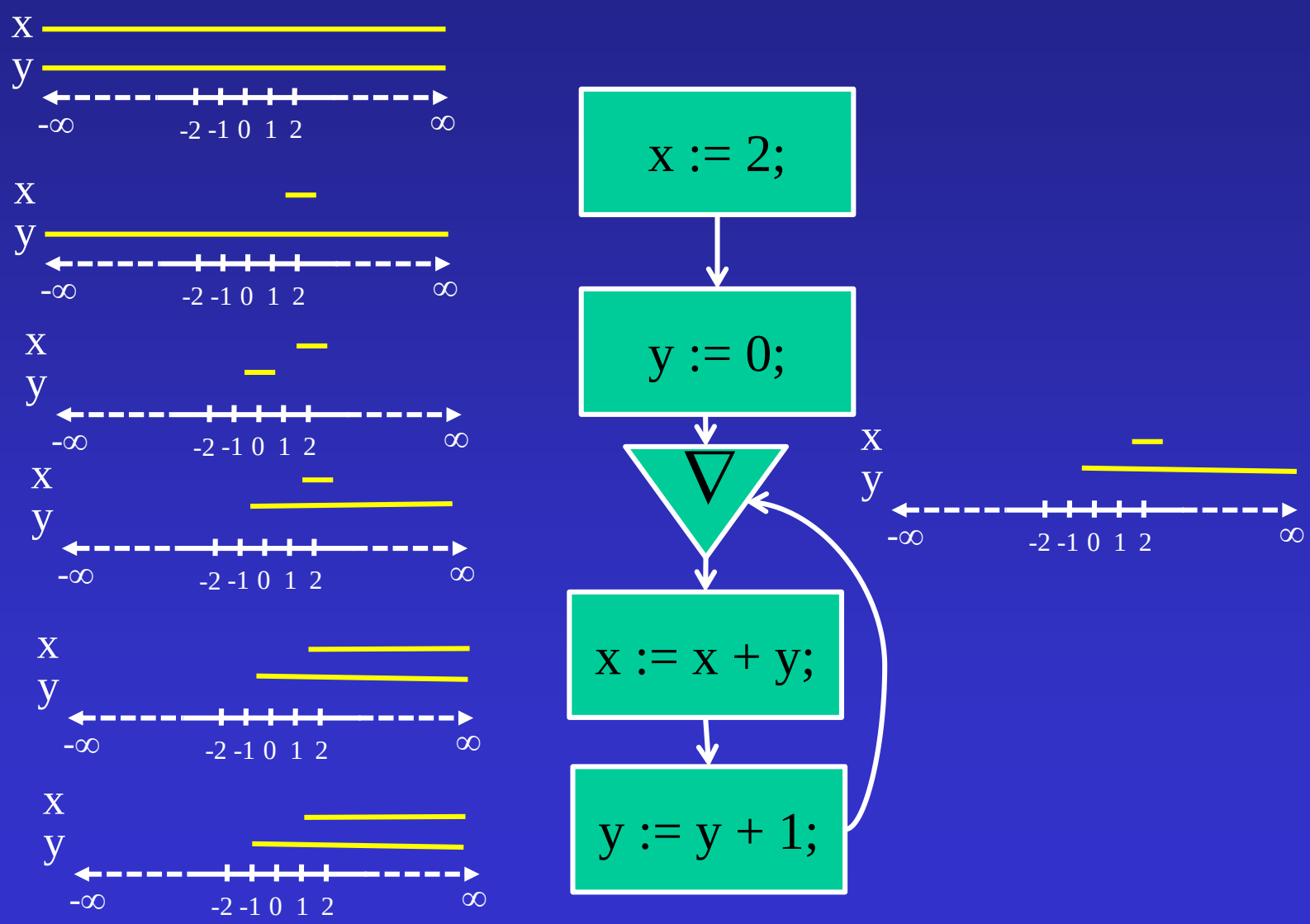
Infer Inductive Invariants via AI



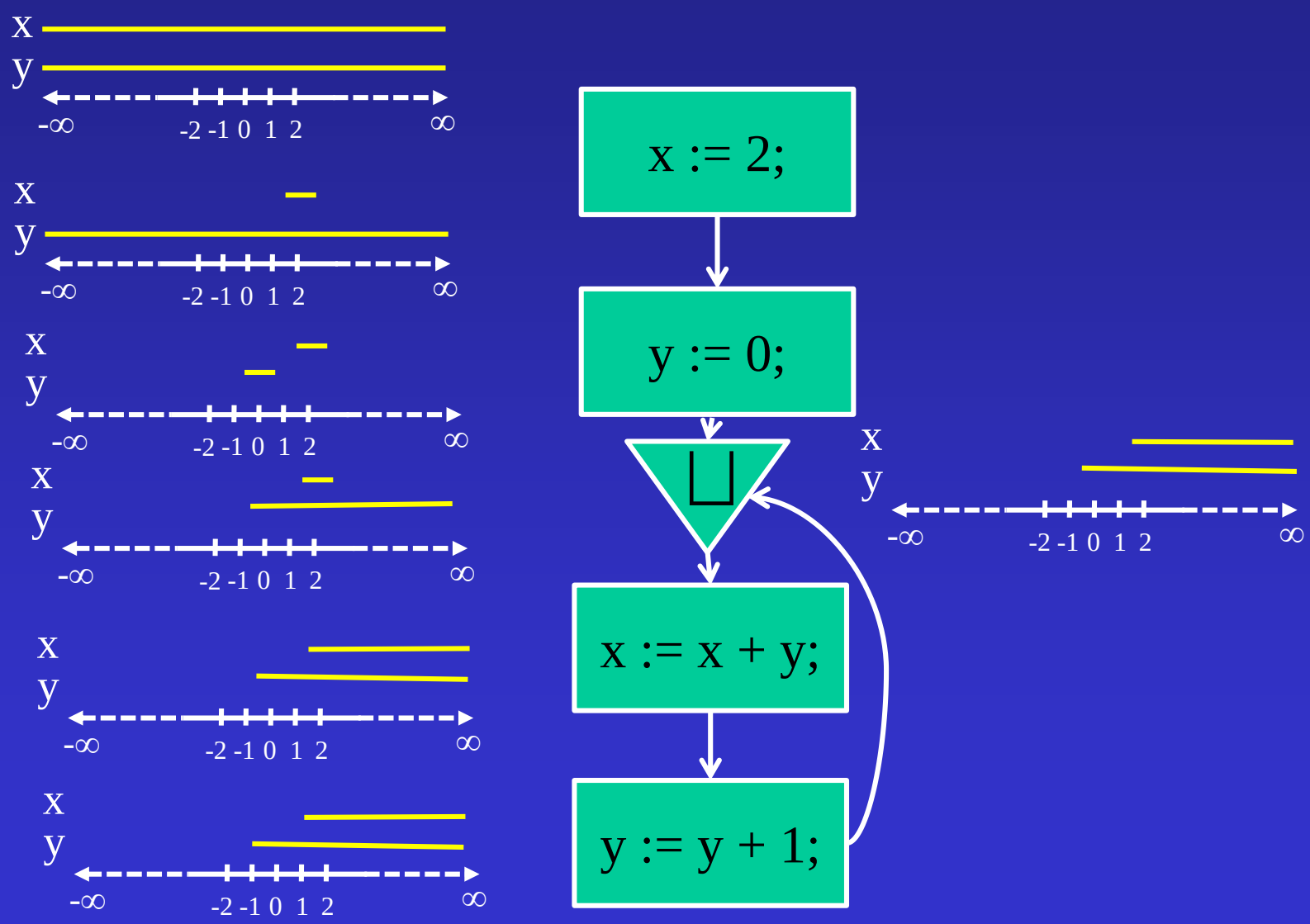
Infer Inductive Invariants via AI



Infer Inductive Invariants via AI



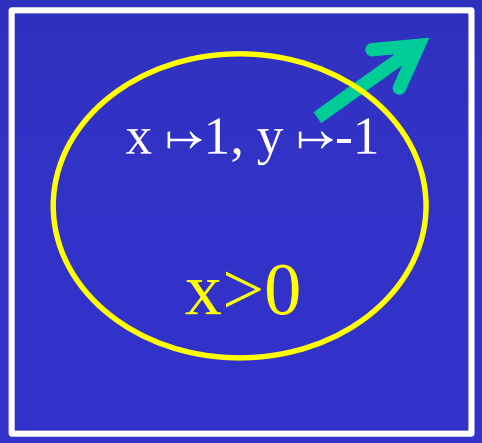
Infer Inductive Invariants via AI



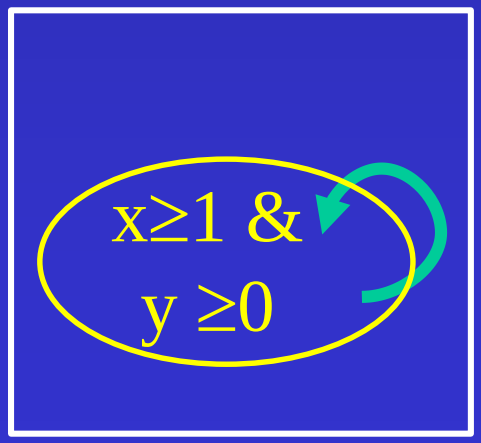
AI Infers Inductive Invariants

```
x := 2; y := 0;
while true do
        assert x > 0 ;
        x := x + y;
        y := y + 1
```

Non-inductive



Inductive



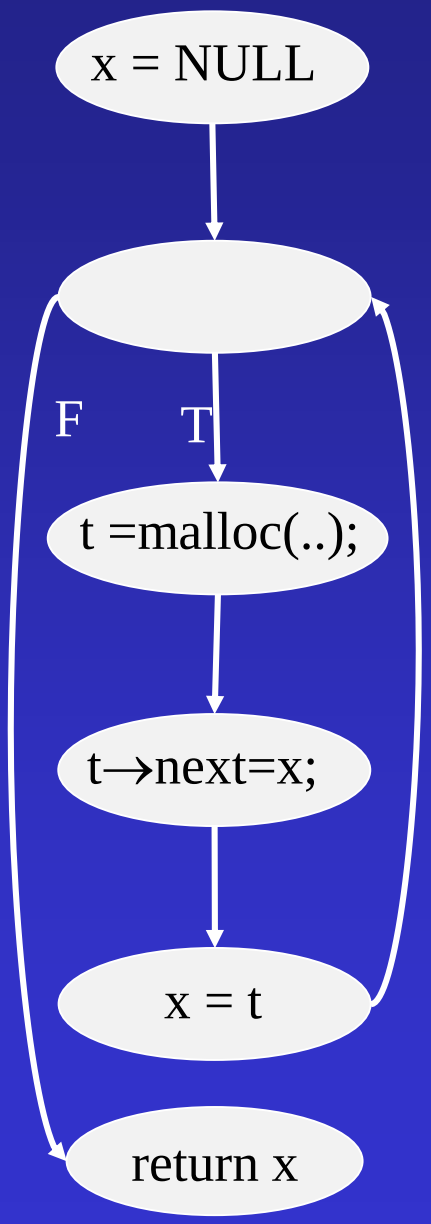
Original Problem: Shape Analysis (Jones and Muchnick 1981)

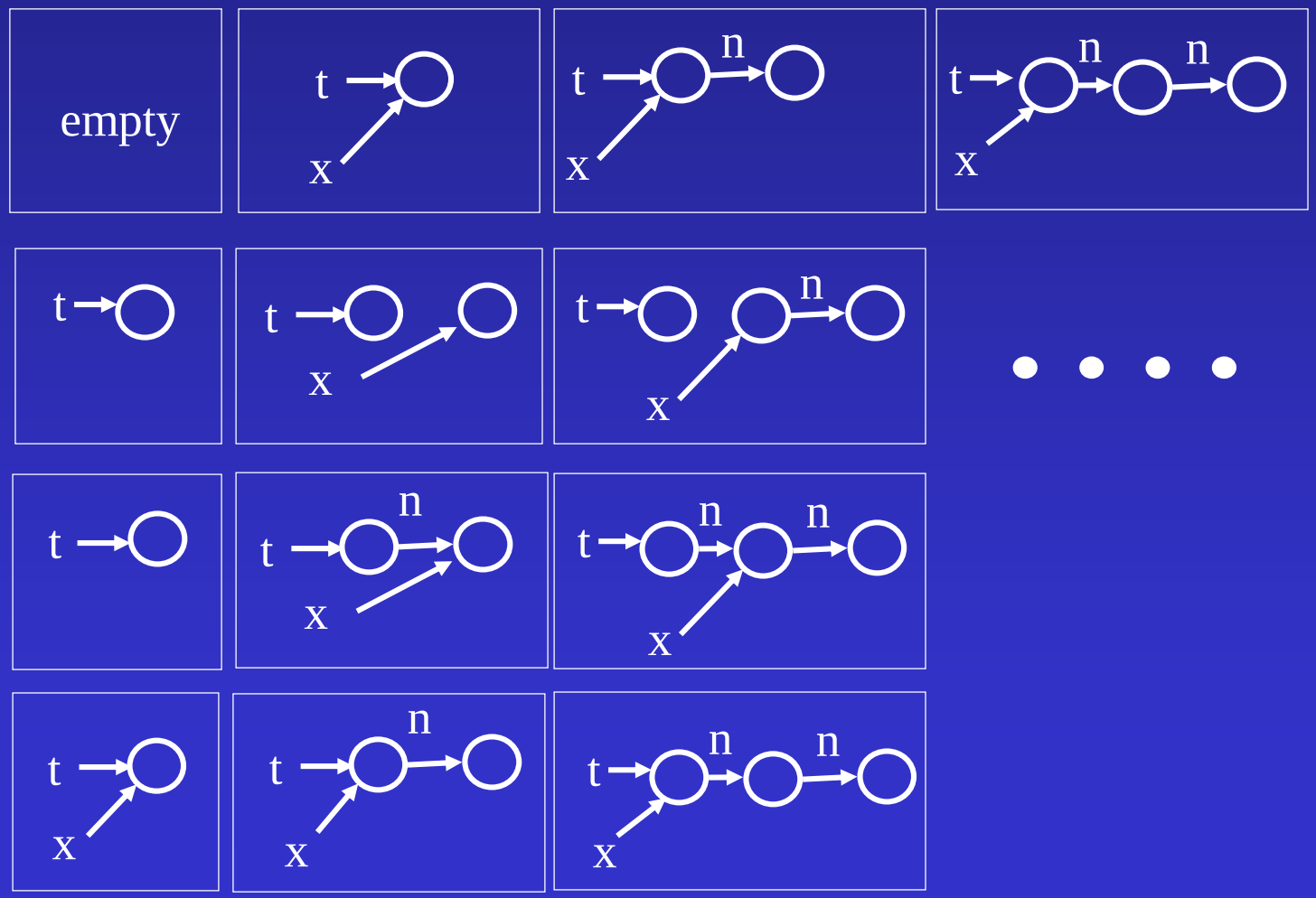
- Characterize dynamically allocated data
  - *x* points to an acyclic list, cyclic list, tree, dag, etc.
  - show that data-structure invariants hold
- Identify may-alias relationships
- Establish "disjointedness" properties
  - *x* and *y* point to structures that do not share cells
- Memory Safety
  - No null and dangling de-references
  - No memory leaks
- In OO programming
  - Everything is in the heap ➔ requires shape analysis

Why Bother?

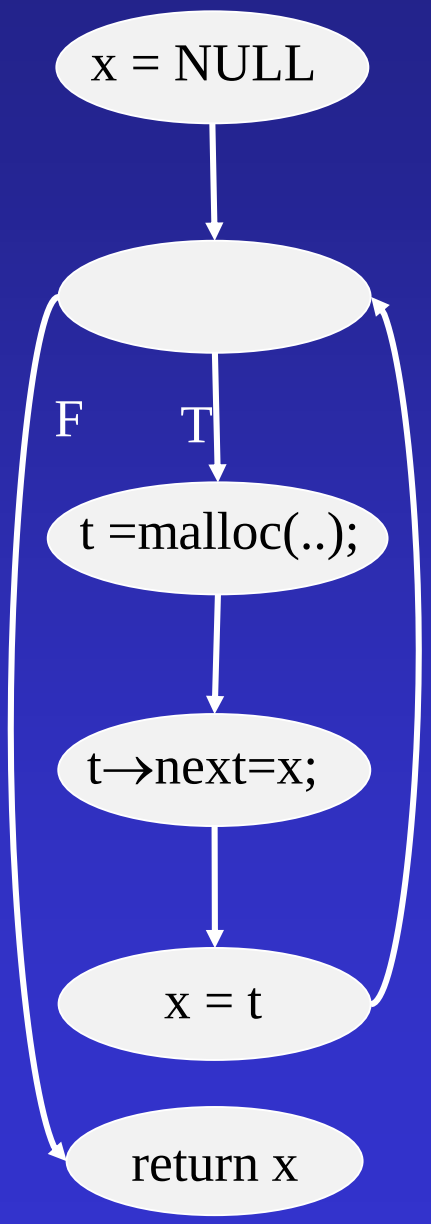
```
    int *p,  *q;
    q = (int *) malloc();
    p = q;
l1: *p = 5;
     p = (int *) malloc();
l2: printf(*q);  /* printf(5) */
```

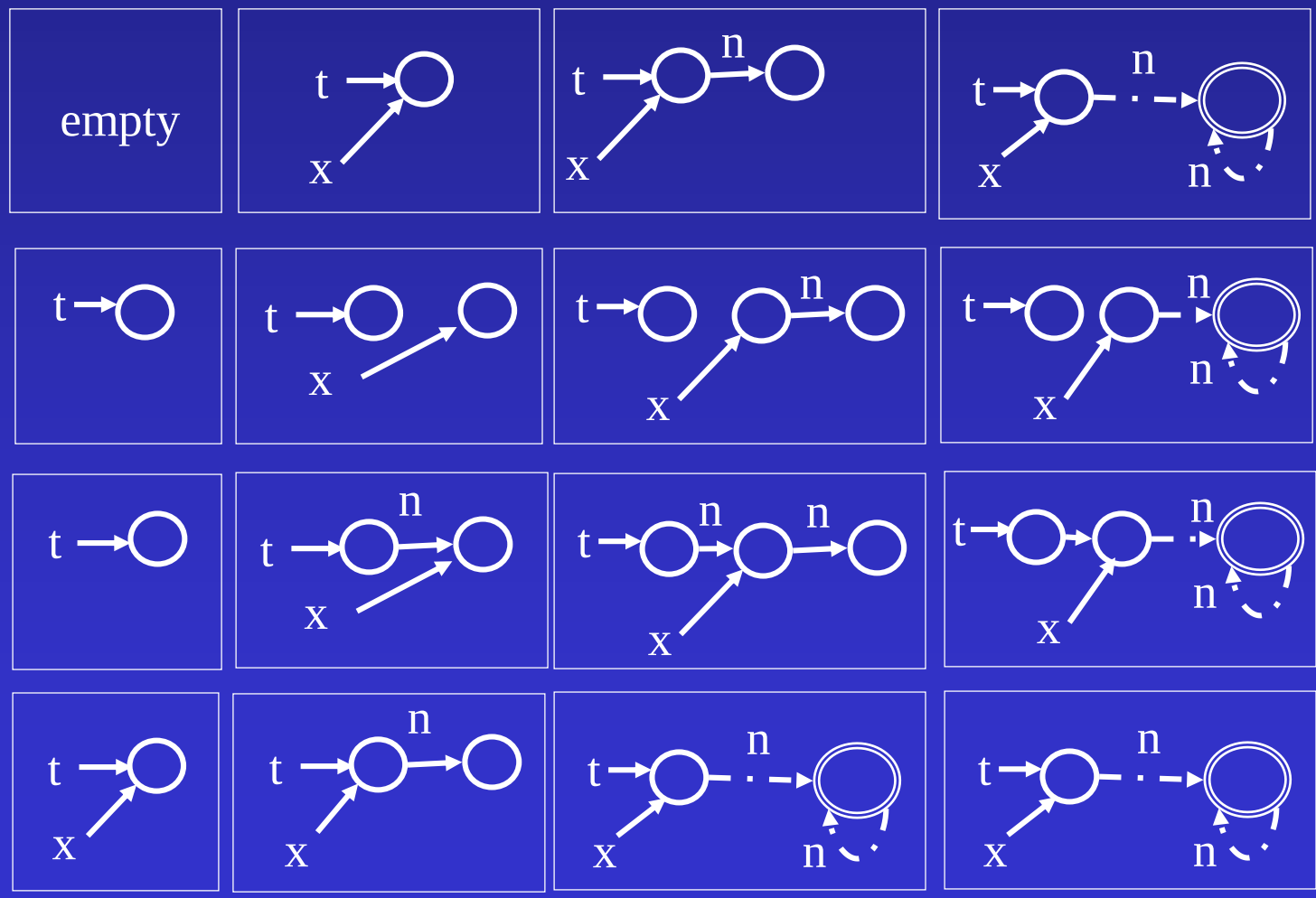
Example: Concrete Interpretation





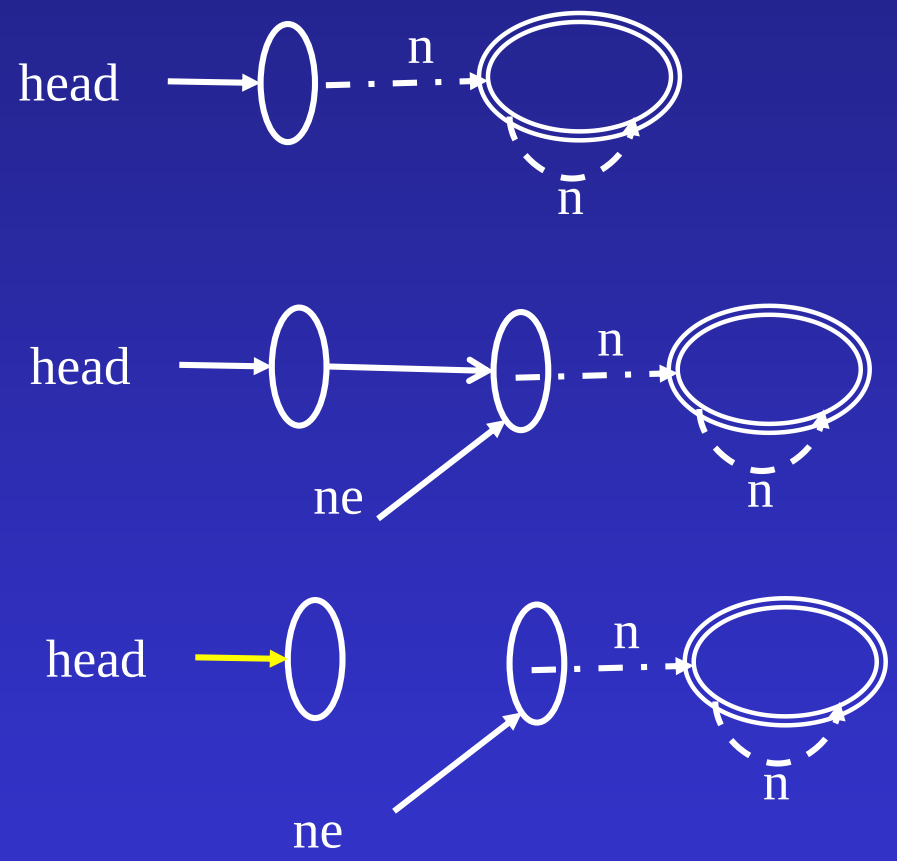
Example: Abstract Interpretation





Memory Leakage

```
List reverse(Element *head)
{
    List rev, ne;
    rev = NULL;
    while (head != NULL) {
        ne = head →next;
        head → next = rev;
        head = ne;
        rev = head;
    }
    return rev;
}
```



leakage of address pointed to by head

Memory Leakage

```
Element* reverse(Element *head)
{
   Element *rev, *ne;
    rev = NULL;
    while (head != NULL) {
          ne = head → next;
          head → next = rev;
          rev = head;
          head = ne;
    }
    return rev;
}
```

No memory leaks

Mark and Sweep

```
void Mark(Node root) {
  if (root != NULL) {
    pending = ∅
    pending = pending ∪ {root}
    marked = ∅
    while (pending ≠ ∅) {
      x = SelectAndRemove(pending)
      marked = marked ∪ {x}
      t = x → left
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
      t = x → right
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
    }
  }
  assert(marked == Reachset(root))
}
```

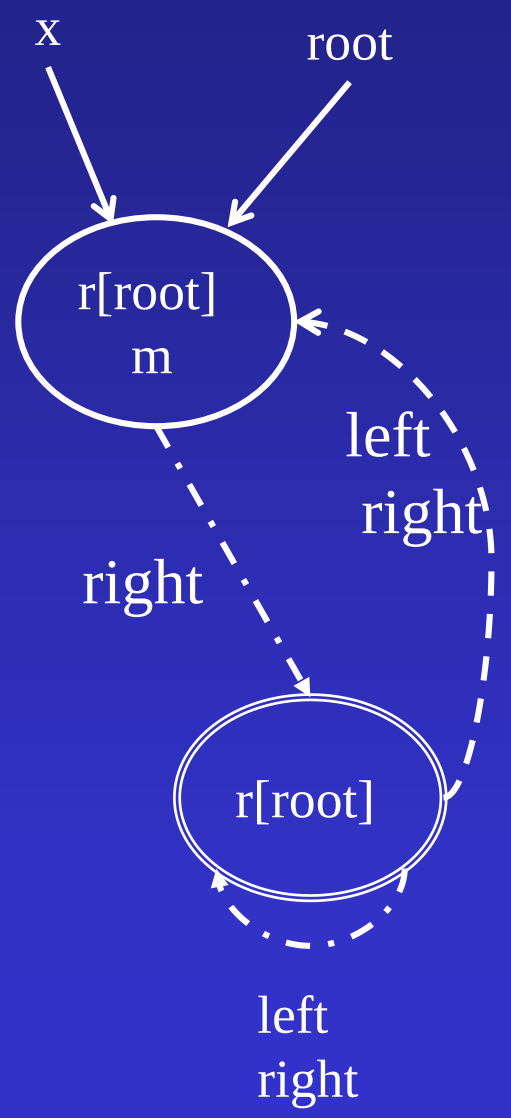
```
void Sweep() {
  unexplored = Universe
  collected = ∅
  while (unexplored ≠ ∅) {
    x = SelectAndRemove(unexplored)
    if (x ∉ marked)
      collected = collected ∪ {x}
  }
  assert(collected ==
          Universe – Reachset(root)
        )
}
```

$\forall v$: marked(v) $\Leftrightarrow$ reach[root](v)

Example: Mark

```
void Mark(Node root) {
  if (root != NULL) {
    pending = ∅
    pending = pending ∪ {root}
    marked = ∅
    while (pending ≠ ∅) {
      x = SelectAndRemove(pending)
      marked = marked ∪ {x}
      t = x → left
      if (t ≠ NULL)
        if (t ∉ marked)
          pending = pending ∪ {t}
/*    t = x → right
 *    if (t ≠ NULL)
 *      if (t ∉ marked)
 *        pending = pending ∪ {t}
 */  }
  }
  assert(marked = = Reachset(root))
}
```

Bug Found



- There may exist an individual that is reachable from the root, but not marked

$$r[root](root) \wedge \neg p(root) \wedge m(root) \wedge$$
$$\exists e: r[root](e) \wedge \neg m(e) \wedge \neg root(e) \wedge \neg p(e)$$
$$\forall r, e: (root(r) \wedge r[root](r) \wedge \neg p(r) \wedge m(r) \wedge$$
$$r[root](e) \wedge \neg m(e)) \wedge \neg root(e) \wedge \neg p(e))$$
$$\rightarrow \neg left(r,e)$$

Properties Proved

Program	Properties	#Graphs	Seconds
LindstromScan	CL, DI	1285	8.2
LindstromScan	CL, DI, IS, TE	183564	2185
SetRemove	CL, DI, SO	13180	106
SetInsert	CL, DI, SO	299	1.75
DeleteSortedTree	CL, DI	2429	6.24
DeleteSortedTree	CL, DI, SO	30754	104
InsertSortedTree	CL, DI	177	0.85
InsertSortedTree	CL, DI, SO	1103	2.5
InsertAVLttree	CL, DI, SO	1855	27.4
RecQuickSot	CL, DI, SO	5585	9.2

CL=memory safety DI=data structure invariant TE=termination SO=sorted

Success Story: The SLAM/SDV Project MSR

- Tool for finding possible bugs in Windows device drivers
- Complicated back-out protocols in driver APIs when events cancelled or interrupted

"Things like even software verification, this has been the Holy Grail of computer science for many decades but now in some very key areas, for example, driver verification we're building tools that can do actual proof about the software and how it works in order to guarantee the reliability."
Bill Gates, April 18, 2002. Keynote address **at** WinHec 2002

[
E
[
Automatic Predicate Abstraction of
[POPL'04] T. A. Henzinger, R. Jhala, R. Majumdar, K. L. McMillan: Abstractions from proofs

Type Checking

Benjamin Pierce. Types and Programming Languages

August 2005

As a Malaysia Airlines jetliner cruised from Perth,
Australia, to Kuala Lumpur, Malaysia,
one evening last August, it suddenly took on a mind of its own and
zoomed 3,000 feet upward.
The captain disconnected the autopilot and pointed the Boe
777's nose down to avoid stalling, but was jerked into a ste
He throttled back sharply on both engines, trying to slow th
Instead, the jet raced into another climb.
The crew eventually regained control and manually flew their
177 passengers safely back to Australia.

Investigators quickly discovered the reason for the plane's
roller-coaster ride 38,000 feet above the Indian Ocean.
A defective software program had provided incorrect data about the
aircraft's speed and acceleration, confusing flight computers. August 2005

Error Detection

- Early error detection
  - Logical errors
  - Interface errors
  - Dimension analysis
  - Effectiveness also depends on the programmer
  - Can be used for code maintenance

Type Systems

- A tractable syntactic method for proving absence of certain program behaviors by classifying phrases according to the kinds they compute
- Examples
  - Whenever f is called, its argument must be integer
  - The arguments of f are not aliased
  - The types of dimensions must match
  - …

What is a type

- A denotation of set of values
  - Int
  - Bool
  - …
- A set of legal operations

Static Type Checking

- Performed at compile-time
- Conservative (sound but incomplete)
  - if <complex test> then 5 else <type error>
- Usually limited to simple properties
  - Prevents runtime errors
  - Enforce modularity
  - Protects user-defined abstractions
  - Allows tractable analysis
    - But worst case complexity can be high
- Properties beyond scope (usually)
  - Array out of bound
  - Division by zero
  - Non null reference

Abstraction

- Types define interface between different software components
- Enforces disciplined programming
- Ease software integration
- Other abstractions exist

Documentation

- Types are useful for reading programs
- Can be used by language tools

Language Safety

- A safe programming language protects its own abstraction
- Can be achieved by type safety
- Type safety for Java was formally proven
  - Recent bug in the soundness of generics

Statically vs. Dynamically Checked Languages

	Statically Checked	Dynamically Checked
Safe	ML, Haskel, Java, C#	Lisp, Scheme, Perl, Python
Unsafe	C, C++	

Efficiency

- Compilers can use types to optimize computations
- Pointer scope
- Region inference

Language Design

- Design the programming language with the type system
- But types incur some notational overhead
- Implicit vs. explicit types
  - The annotation overhead
- Designing libraries is challenging
  - Generics/Polymorphism help

Untyped Arithmetic Expressions

Chapter 3

Untyped Arithmetic Expressions

t ::=	terms
true	constant true
false	constant false
if t then t else t	conditional
0	constant zero
succ t	successor
pred t	predecessor
iszero t	zero test

if false then 0 else 1	1
iszero (pred (succ 0))	true

Untyped Arithmetic Expressions

t ::=	terms
true	constant true
false	constant false
if t then t else t	conditional
0	constant zero
succ t	successor
pred t	predecessor
iszero t	zero test

succ true	type error
if 0 then 0 else 0	type error

Structural Operational Semantics (SOS)

- The mathematical meaning of programs
- A high level definition of interpreter
- Allow inductively proving program properties
- A binary relation on terms
  - $t \rightarrow t'$
    - One step of executing t may yield the value t'
- Inductive definitions of $\rightarrow$
  - Axioms
  - Inference rules
- The meaning of a program is a set of trees
- The actual interpreter can be automatically derived

SOS Axioms for the Simple Language

t ::=	terms
true	constant true
false	constant false
if t then t else t	conditional
0	constant zero
succ t	successor
pred t	predecessor
iszero t	zero test

SOS Inference for the Simple Language

t ::=	terms
true	constant true
false	constant false
if t then t else t	conditional
0	constant zero
succ t	successor
pred t	predecessor
iszero t	zero test

SOS rules for Untyped Arithmetic Expressions

$$\text{if true then } t_1 \text{ else } t_2 \rightarrow t_1 \quad \text{(E-IFTRUE)}$$

$$\text{if false then } t_1 \text{ else } t_2 \rightarrow t_2 \quad \text{(E-IFFALSE)}$$

$$\frac{t_1 \rightarrow t'_1}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 \rightarrow \text{if } t'_1 \text{ then } t_2 \text{ else } t_3} \quad \text{(E-IF)}$$

$$\frac{t_1 \rightarrow t'_1}{\text{succ } t_1 \rightarrow \text{succ } t'_1} \quad \text{(E-SUCC)}$$

$$\frac{t_1 \rightarrow t'_1}{\text{pred } t_1 \rightarrow \text{pred } t'_1} \quad \text{(E-PRED)}$$

$$\text{pred } 0 \rightarrow 0 \quad \text{(E-PREDZERO)}$$

$$\text{pred (succ } t) \rightarrow t \quad \text{(E-PREDSUCC)}$$

$$\frac{t_1 \rightarrow t'_1}{\text{iszero } t_1 \rightarrow \text{iszero } t'_1} \quad \text{(E-ISZERO)}$$

$$\text{iszero } 0 \rightarrow \text{true} \quad \text{(E-ISZEROZERO)}$$

$$\text{iszero succ } t \rightarrow \text{false} \quad \text{(E-ISZERONZERO)}$$

Examples

if false then 0 else 1

iszero (pred (succ 0))

succ true

if 0 then 0 else 0

if iszero (succ true) then 0 else 1

Properties of the semantics

- Partial
- Determinism
  - $t_1 \rightarrow t_2 \ \wedge t_1 \rightarrow t_3 \Rightarrow t_2 = t_3$
- Reflexive transitive closure
  - $t \rightarrow^* t'$ if either $t = t'$ or there exists $t_0, t_1, \ldots, t_n$ such that $t=t_0$, $t' = t_n$ and for every $0 \leq i < n$: $t_i \rightarrow t_{i+1}$
- Semantic meaning
  - $[\![\,]\!]$: Terms $\rightharpoonup$ Nat $\cup$ Bool
  - $[\![t]\!] = t'$ if $t' \in$ Nat $\cup$ Bool $\wedge\ t \rightarrow^* t'$

Typed Arithmetic Expressions

Chapter 8

Well Typed Programs

- A set of type rules conservatively define well typed programs
- The typing relation is the smallest binary relation between terms and types
  - in terms of inclusion
- A term t is typable (well typed) if there exists some type T such that t : T
- The type checking problem is to determine for a given term t and type T if t : T
- The type inference problem is to infer for a given term t a type T such that t : T

Type Safety

- Stuck terms: Undefined Semantics
  - $\neg\exists t' : t \rightarrow t'$
- The goal of the type system is to ensure at compile-time that no stuck ever occurs at runtime
- Type Safety (soundness)
  - Progress: A well-typed term t never gets stuck
    - Either it has value or there exists t' such that $t \rightarrow t'$
  - Preservation: (subject reduction)
    - If well type term takes a step in evaluation, then the resulting term is also well typed

Typed Arithmetic Expressions

t ::=	terms
true	constant true
false	constant false
if t then t else t	conditional
0	constant zero
succ t	successor
pred t	predecessor
iszero t	zero test

v ::=	values
true	true value
false	false value
nv	numeric value

nv ::=	numeric values
0	zero value
succ nv	successor value

Type Rules for Booleans

T ::=		types
	Bool	type of Boolean

$$t : T$$

$$\text{true} : \text{Bool} \quad \text{(T-TRUE)}$$

$$\text{false} : \text{Bool} \quad \text{(T-FALSE)}$$

$$\frac{t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 : T} \quad \text{(T-IF)}$$

Type Rules for Numbers

T ::=	types
Nat	type of Natural numbers

$$t : T$$

$$0 : Nat \ (T\text{-}ZERO)$$

$$\frac{t_1 : Nat}{succ(t_1) : Nat} \ T\text{-}SUCC$$

$$\frac{t_1 : Nat}{pred(t_1) : Nat} \ T\text{-}PRED$$

$$\frac{t_1 : Nat}{iszero(t_1) : Bool} \ T\text{-}ISZERO$$

Type Rules for Arithmetic Expressions

true : Bool (T-TRUE)

false : Bool (T-FALSE)

$$\frac{t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 : T} \text{(T-IF)}$$

0 : Nat (T-ZERO)

$$\frac{t_1 : \text{Nat}}{\text{succ}(t_1) : \text{Nat}} \text{T-SUCC}$$

$$\frac{t_1 : \text{Nat}}{\text{pred}(t_1) : \text{Nat}} \text{T-PRED}$$

$$\frac{t_1 : \text{Nat}}{\text{iszero}(t_1) : \text{Bool}} \text{T-ISZERO}$$

Examples

if false then 0 else 1

if false then succ true else 1

if iszero 0 then 0 else 1

iszero (pred (succ 0))

succ true

if 0 then 0 else 0

if iszero (succ true) then 0 else 1

Uniqueness of Types

- Each term t has at most one type
  - If t is typable then
    - its type is unique
    - There is a unique type derivation tree for t
- Does not hold for general languages
  - Need a partial order on types
  - Unique most general type

Type Safety

Progress : If t is well typed then either t is a value or for some t': $t \rightarrow t'$

Preservation: if $t : T$ and $t \rightarrow t'$ then $t' : T$

nv	::=	numeric values	
		0	zero value
		succ nv	successor value

Language Restrictions so far

- Simple expression language
- Fixed number of types
- No loops/recursion
- No variables/states
- No memory allocation

Summary Type Systems

- Type systems provide a useful mechanism for conservatively enforcing certain safety properties
  - Can be combined with runtime systems and static program analysis
- Interacts with the programmer
- A lot of interesting theory
- Another alternative is static program analysis
  - Infer abstractions of values at every program point

Tentative Schedule

25/10	Overview
1/11	Inductive Definitions & Haskel
8/11	Monads and Continuation
15/11	Operational Semantics
22,27/11	Denotational Semantics
6, 13/12	Deductive Verification
27/12, 3/1	Abstract Interpretation
10, 17/1	Type Checking/Type inference