Lecture 14

Pointer Analysis

- Basics
- Design Options
- Pointer Analysis Algorithms
- Pointer Analysis Using BDDs
- Probabilistic Pointer Analysis

[ALSU 12.4, 12.6-12.7]

Pros and Cons of Pointers

- Many procedural languages have pointers
  - e.g., C or C++: `int *p = &x;`
- Pointers are powerful and convenient
  - can build arbitrary data structures
- Pointers can also hinder compiler optimization
  - hard to know where pointers are pointing
  - must be conservative in their presence
- Has inspired much research
  - analyses to decide where pointers are pointing
  - many options and trade-offs
  - open problem: a scalable accurate analysis

I. Pointer Analysis Basics: Aliases

- Two variables are aliases if:
  - they reference the same memory location
- More useful:
  - prove variables reference different locations

What are the Alias sets?

```
int x,y;
int *p = &x;
int *q = &y;
int *r = p;
int **s = &q;
```

{x, *p, *r}

{y, *q, **s}

{q, *s}

p and q point to different locations

The Pointer Alias Analysis Problem

- Decide for every pair of pointers at every program point:
  - do they point to the same memory location?
- A difficult problem
  - shown to be undecidable by Landi, 1992
- Correctness:
  - report all pairs of pointers which do/may alias
- Ambiguous:
  - two pointers which may or may not alias
- Accuracy/Precision:
  - how few pairs of pointers are reported while remaining correct
  - i.e., reduce ambiguity to improve accuracy

Many Uses of Pointer Analysis

- Basic compiler optimizations
  - register allocation, CSE, dead code elimination, live variables, instruction scheduling, loop invariant code motion, redundant load/store elimination
- Parallelization
  - instruction-level parallelism
  - thread-level parallelism
- Behavioral synthesis
  - automatically converting C-code into gates
- Error detection and program understanding
  - memory leaks, wild pointers, security holes

Challenges for Pointer Analysis

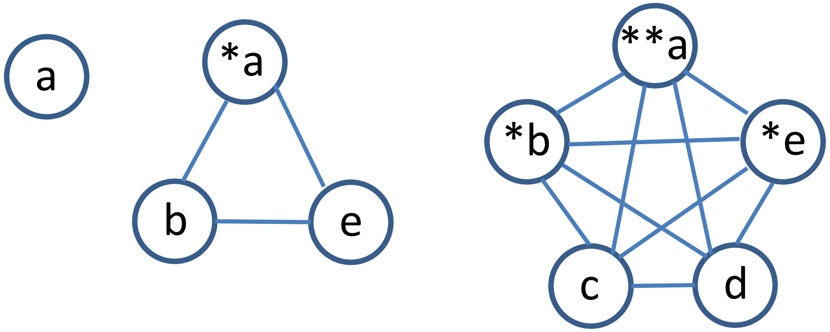
- Complexity: huge in space and time
  - compare every pointer with every other pointer
  - at every program point
  - potentially considering all program paths to that point
- Scalability vs accuracy trade-off
  - different analyses motivated for different purposes
  - many useful algorithms (adds to confusion)
- Coding corner cases
  - pointer arithmetic (*p++), casting, function pointers, long-jumps
- Whole program?
  - most analysis algorithms require the entire program
  - library code? optimizing at link-time only?

II. Pointer Analysis: Design Options

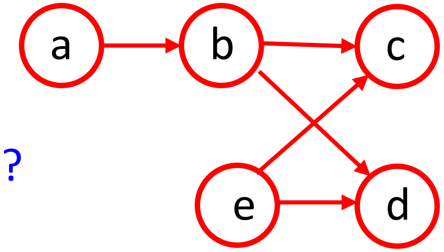
- Representation
- Heap modeling
- Aggregate modeling (e.g., arrays, structs)
- Flow sensitivity
- Context sensitivity

Representation

- Track pointer aliases
  - <*a, b>, <*a, e>, <b, e>, <**a, c>, <**a, d>, …
  - More precise, less efficient



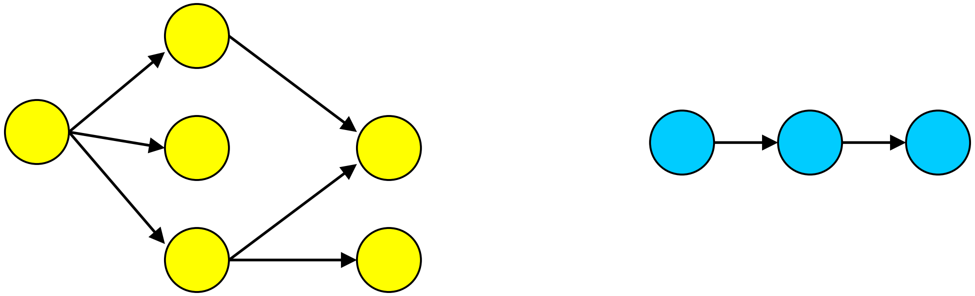
- Track points-to information
  - <a, b>, <b, c>, <b, d>, <e, c>, <e, d>
  - Less precise, more efficient. Why?



```
a = &b;
b = &c;
b = &d;
e = b;
```

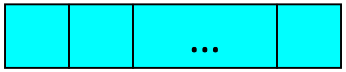
Heap Modeling Options

- Heap merged
  - i.e. “no heap modeling”
- Allocation site (any call to malloc/calloc)
  - Consider each to be a unique location
  - Doesn’t differentiate between multiple objects allocated by the same allocation site
- Shape analysis
  - Recognize linked lists, trees, DAGs, etc.



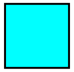
Aggregate Modeling Options

Arrays



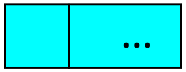
Elements are treated
as individual locations

or



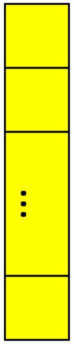
Treat entire array
as a single location

or



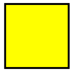
Treat first element
separate from others

Structures



Elements are treated
as individual locations
("field sensitive")

or



Treat entire structure as a
single location

What are the trade-offs?

Flow Sensitivity Options

- Flow insensitive
  - The order of statements doesn't matter
    - Result of analysis is the same regardless of statement order
  - Uses a single global state to store results as they are computed
  - Fast, but not very accurate
- Flow sensitive
  - The order of the statements matter
  - Need a control flow graph
  - Must store results for each program point
  - Improves accuracy
- Path sensitive
  - Each path in a control flow graph is considered
  - If-then-else implies mutually exclusive paths

Flow Sensitivity Example

(assuming allocation-site heap modeling)

```
S1: a = malloc(…);
S2: b = malloc(…);
S3: a = b;
S4: a = malloc(…);
S5: if(c)
       a = b;
S6: if(!c)
       a = malloc(…);
S7: … = *a;
```

Flow Insensitive

$a_{S7} \rightarrow$ {heapS1, heapS2, heapS4, heapS6}

Flow Sensitive

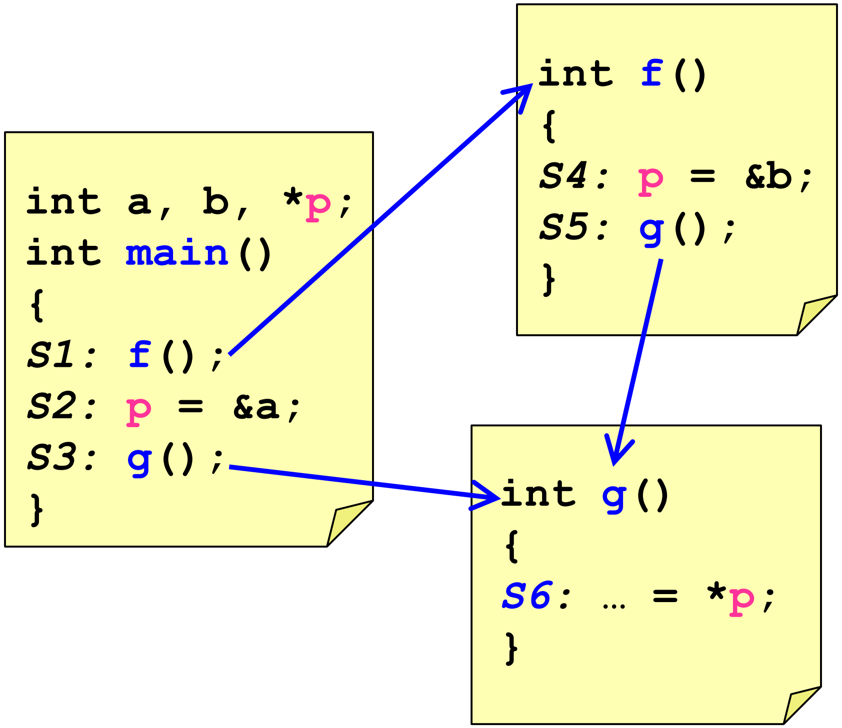
$a_{S7} \rightarrow$ {heapS2, heapS4, heapS6}

Path Sensitive

$a_{S7} \rightarrow$ {heapS2, heapS6}

Context Sensitivity Options

- Context insensitive/sensitive (interprocedural analysis)
  - whether to consider different calling contexts
  - e.g., what are the possibilities for **`p`** at **`S6`**?



```
int a, b, *p;
int main()
{
S1: f();
S2: p = &a;
S3: g();
}
```

```
int f()
{
S4: p = &b;
S5: g();
}
```

```
int g()
{
S6: … = *p;
}
```

Context Insensitive:

$p_{S6} \Rightarrow \{a,b\}$

Context Sensitive:

Called from S3: $p_{S6} \Rightarrow \{a\}$

Called from S5: $p_{S6} \Rightarrow \{b\}$

Pointer Alias Analysis Algorithms

Extensive Literature:

- *"Program Analysis and Specialization for the C Programming Language"*, Andersen, Technical Report, 1994
- *"Context-sensitive interprocedural points-to analysis in the presence of function pointers"*, Emami et al., PLDI 1994
- *"Points-to analysis in almost linear time"*, Steensgaard, POPL 1996
- *"Which pointer analysis should I use?"*, Hind et al., ISSTA 2000
- *"Pointer analysis: haven't we solved this problem yet?"*, Hind, PASTE 2001
- …
- "*Introspective analysis: context-sensitivity, across the board*", Smaragdakis et al., PLDI 2014
- "*Sparse flow-sensitive pointer analysis for multithreaded programs*", Sui et al., CGO 2016
- "*Symbolic range analysis of pointers*", Paisante et al., CGO 2016

Address Taken

- Basic, fast, ultra-conservative algorithm
  - flow-insensitive, context-insensitive
  - often used in production compilers
- Algorithm:
  - Generate the set of all variables whose addresses are assigned to another variable.
  - Assume that any pointer can potentially point to any variable in that set.
- Complexity: O(n) - linear in size of program
- Accuracy: very imprecise

Address Taken Example

```
T *p, *q, *r;

int main() {
S1: p = alloc(T);
    f();
    g(&p);
S4: p = alloc(T);
S5: … = *p;
}
```

```
void f() {
S6: q = alloc(T);
    g(&q);
S8: r = alloc(T);
}
```

```
g(T **fp) {
    T local;
    if(…)
s9:     p = &local;
}
```

p_{S5} = {heapS1, p, heapS4, heapS6, q, heapS8, local}

Andersen's Algorithm

- Flow-insensitive, context-insensitive, iterative
- Representation:
  - one points-to graph for entire program
  - each node represents exactly one location
- For each statement, build the points-to graph:

`y = &x`	`y` points-to `x`
`y = x`	if `x` points-to `w` then `y` points-to `w`
`*y = x`	if `y` points-to `z` and `x` points-to `w` then `z` points-to `w`
`y = *x`	if `x` points-to `z` and `z` points-to `w` then `y` points-to `w`

- Iterate until graph no longer changes
- Worst case complexity: $O(n^3)$, where n = program size

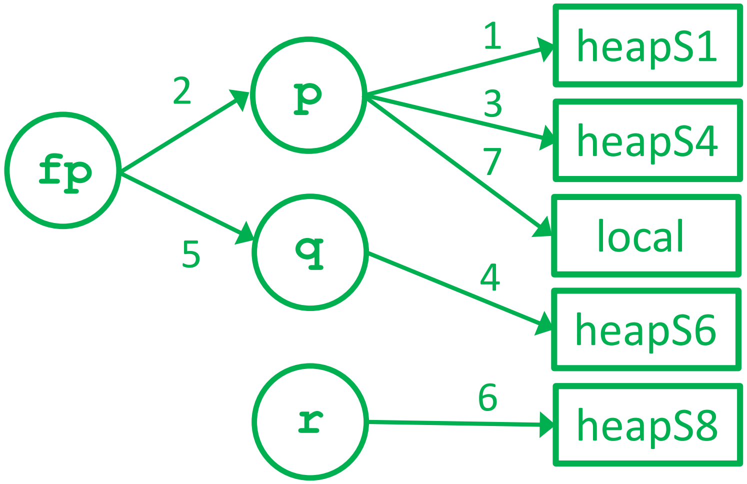
Andersen Example

```
  T *p, *q, *r;

  int main() {
1 S1: p = alloc(T);
      f();
2     g(&p);
3 S4: p = alloc(T);
  S5: … = *p;
  }
```

```
  void f() {
4 S6: q = alloc(T);
5     g(&q);
6 S8: r = alloc(T);
  }
```

```
  g(T **fp) {
      T local;
      if(…)
7 s9:     p = &local;
  }
```



p_{S5} = {heapS1, heapS4, local}

Steensgaard's Algorithm

- Flow-insensitive, context-insensitive
- Representation:
  - a compact points-to graph for entire program
    - each node can represent multiple locations
    - but can only point to one other node
      - i.e. every node has a fan-out of 1 or 0
- *union-find* data structure implements fan-out
  - "unioning" while finding eliminates need to iterate
- Worst case complexity: nearly O(n) time
  - each union-find operation takes nearly O(1) time
- Precision: less precise than Andersen's

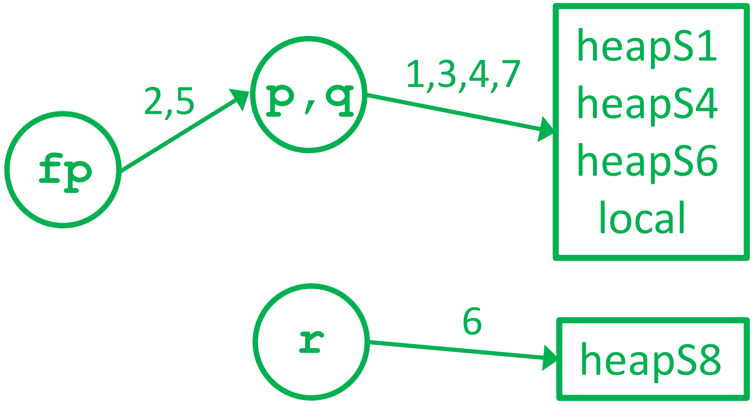
Steensgaard Example

```
  T *p, *q, *r;

  int main() {
1 S1: p = alloc(T);
      f();
2     g(&p);
3 S4: p = alloc(T);
  S5: … = *p;
  }
```

```
  void f() {
4 S6: q = alloc(T);
5      g(&q);
6 S8: r = alloc(T);
  }
```

```
  g(T **fp) {
       T local;
       if(…)
7 s9:      p = &local;
  }
```



p_{S5} = {heapS1, heapS4, heapS6, local}

Example with Flow Sensitivity

```
T *p, *q, *r;

int main() {
S1: p = alloc(T);
    f();
    g(&p);
S4: p = alloc(T);
S5: … = *p;
}
```

```
void f() {
S6: q = alloc(T);
    g(&q);
S8: r = alloc(T);
}
```

```
g(T **fp) {
    T local;
    if(…)
s9:     p = &local;
}
```

p_{S5} = {heapS4}

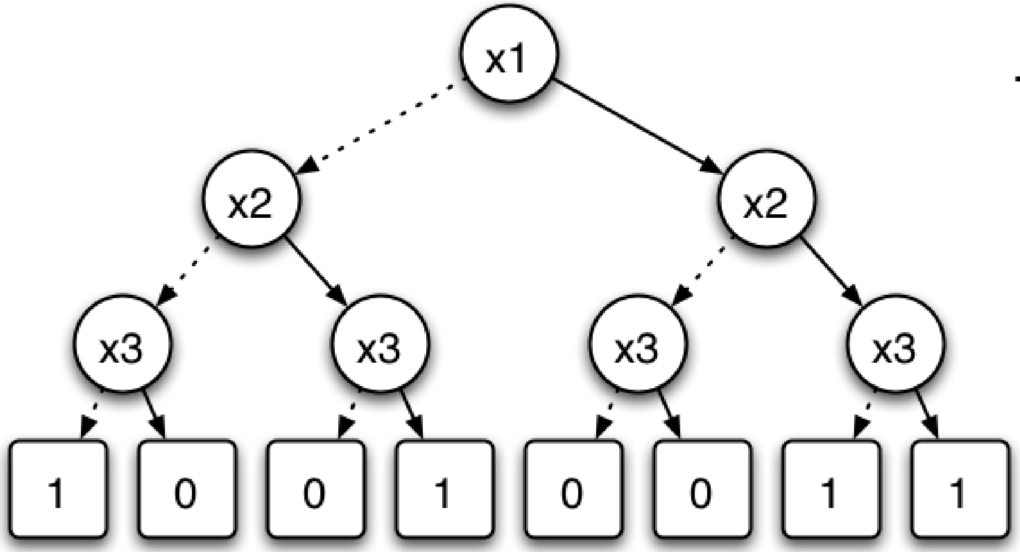
p_{S9} = {local, heapS1}

Pointer Analysis Using BDDs

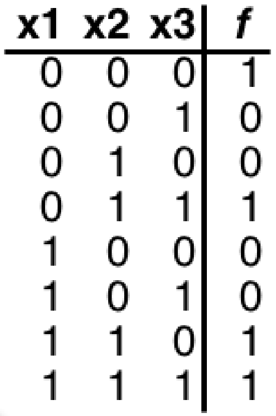
References:

- *“Cloning-based context-sensitive pointer alias analysis using binary decision diagrams”*, Whaley and Lam, PLDI 2004
- *“Symbolic pointer analysis revisited”*, Zhu and Calman, PDLI 2004
- *“Points-to analysis using BDDs”*, Berndl et al, PDLI 2003

Binary Decision Diagram (BDD)

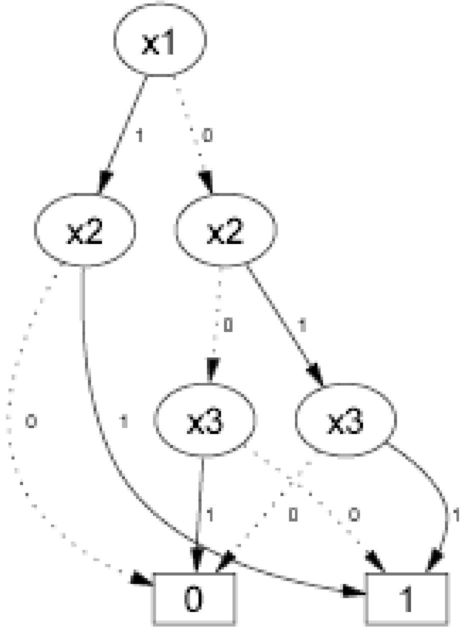


Binary Decision Tree



x1	x2	x3	*f*
0	0	0	1
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

Truth Table



BDD

BDD-Based Pointer Analysis

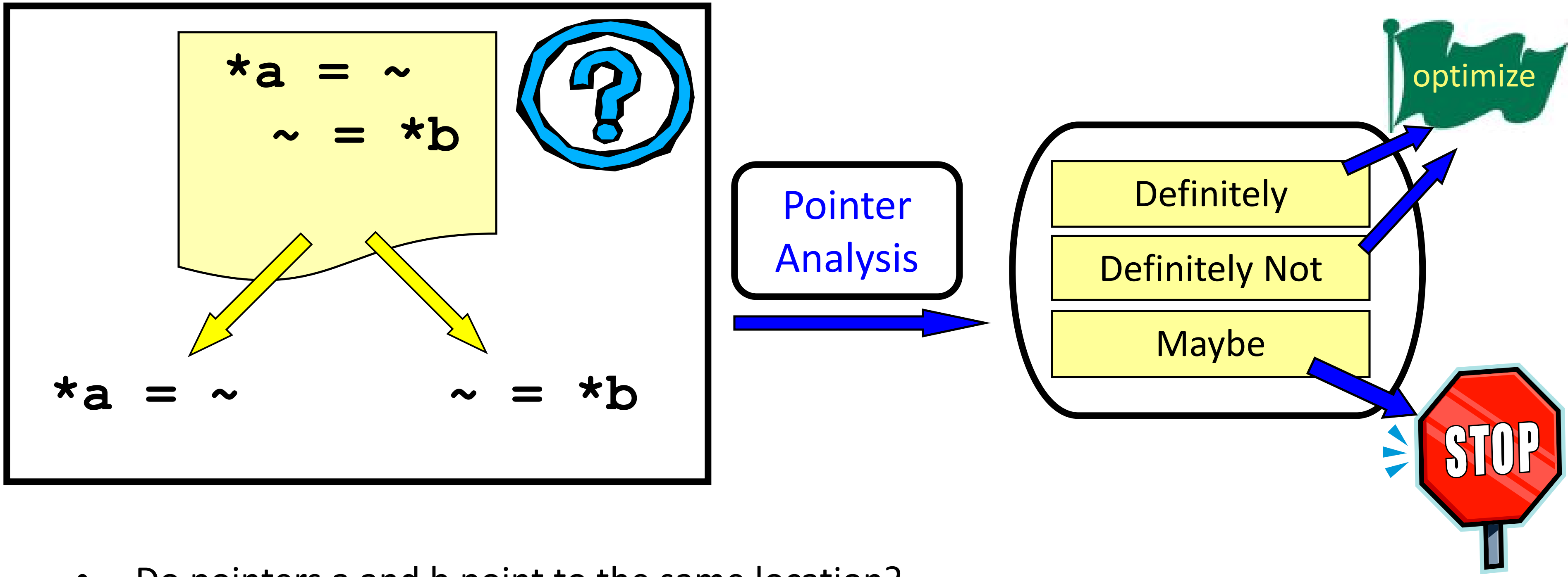
- Use a BDD to represent transfer functions
  - encode procedure as a function of its calling context
  - compact and efficient representation
- Perform context-sensitive, inter-procedural analysis
  - similar to dataflow analysis
  - but across the procedure call graph
- Gives accurate results
  - and scales up to large programs

Probabilistic Pointer Analysis

References:

- *"A Probabilistic Pointer Analysis for Speculative Optimizations"*, DaSilva and Steffan, ASPLOS 2006
- *"Compiler support for speculative multithreading architecture with probabilistic points-to analysis"*, Shen et al., PPoPP 2003
- *"Speculative Alias Analysis for Executable Code"*, Fernandez and Espasa, PACT 2002
- *"A General Compiler Framework for Speculative Optimizations Using Data Speculative Code Motion"*, Dai et al., CGO 2005
- *"Speculative register promotion using Advanced Load Address Table (ALAT)"*, Lin et al., CGO 2003

Pointer Analysis: Yes, No, & Maybe



```
*a = ~
  ~ = *b
```

`*a = ~`   `~ = *b`

Pointer Analysis

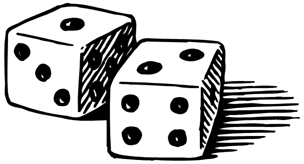
Definitely

Definitely Not

Maybe

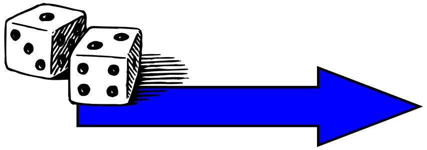
- Do pointers a and b point to the same location?
  - Repeat for every pair of pointers at every program point
- How can we optimize the “maybe” cases?

Let’s Speculate



- Implement a potentially unsafe optimization
  - Verify and Recover if necessary

```
int *a, x;
…
while(…)
{
    x = *a;
    …
}
```



a is *probably* loop invariant

```
int *a, x, tmp;
…
tmp = *a;
while(…)
{
    x = tmp;
    …
}
<verify, recover?>
```

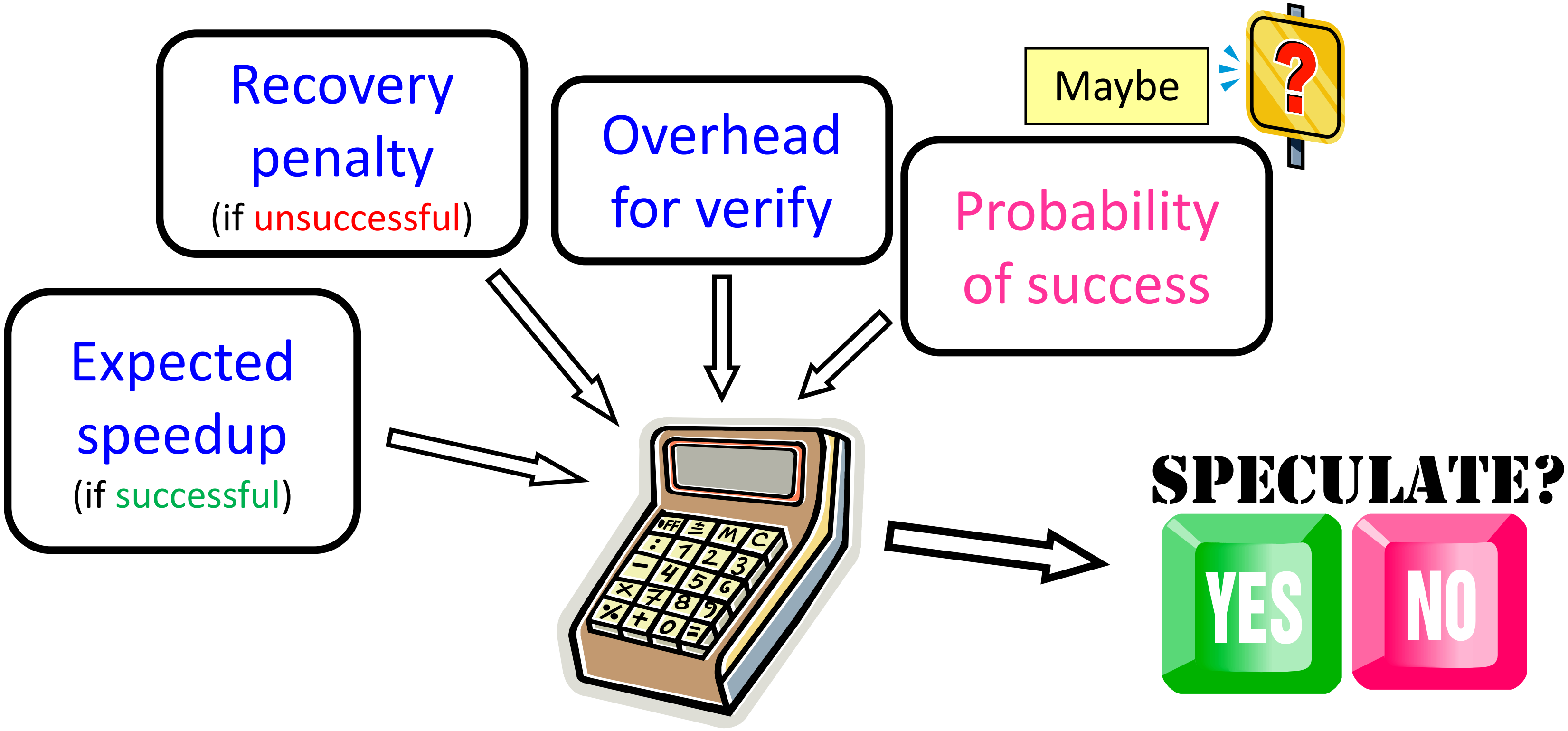
Data Speculative Optimizations

- EPIC Instruction sets
  - Support for speculative load/store instructions (e.g., Itanium)
- Speculative compiler optimizations
  - Dead store elimination, redundancy elimination, copy propagation, strength reduction, register promotion
- Thread-level speculation (TLS)
  - Hardware and compiler support for speculative parallel threads
- Transactional programming
  - Hardware and software support for speculative parallel transactions

Heavy reliance on detailed profile feedback

Can We Quantify “Maybe”?

- Estimate the potential benefit for speculating:



Recovery penalty (if unsuccessful)

Overhead for verify

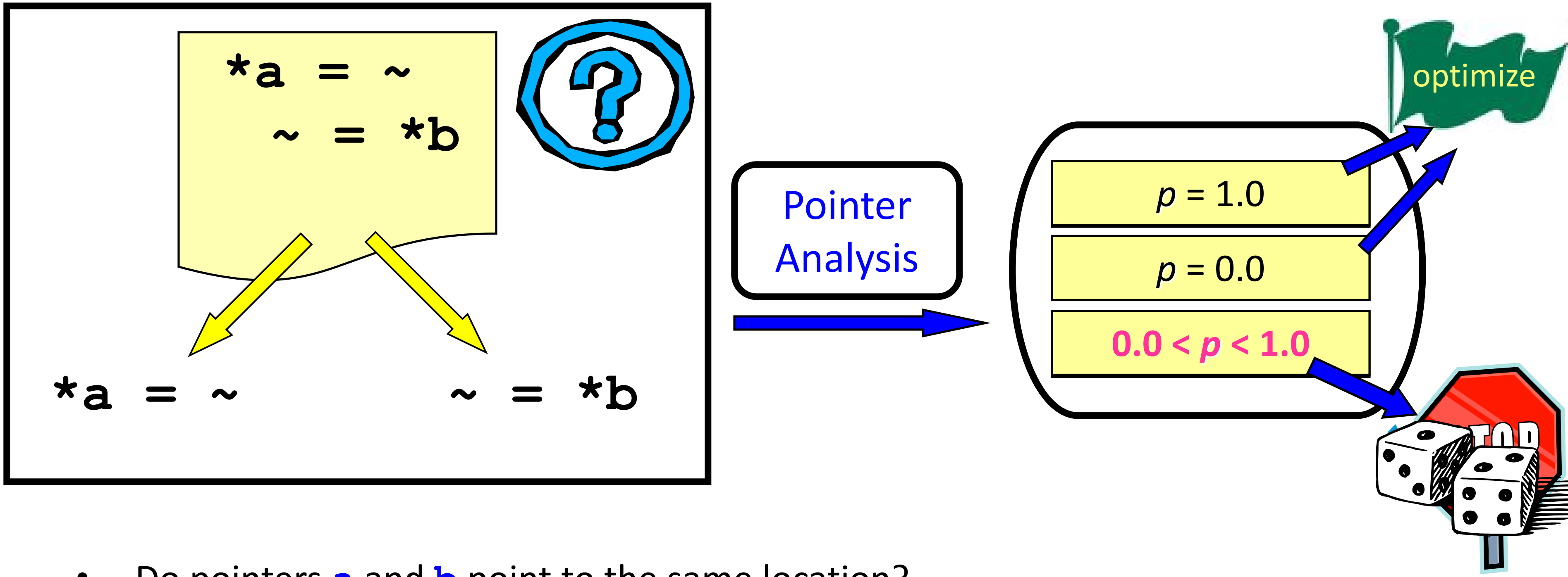
Maybe

Probability of success

Expected speedup (if successful)

Ideally “maybe” should be a probability.

Conventional Pointer Analysis



```
*a = ~
 ~ = *b
```

```
*a = ~          ~ = *b
```

Pointer Analysis

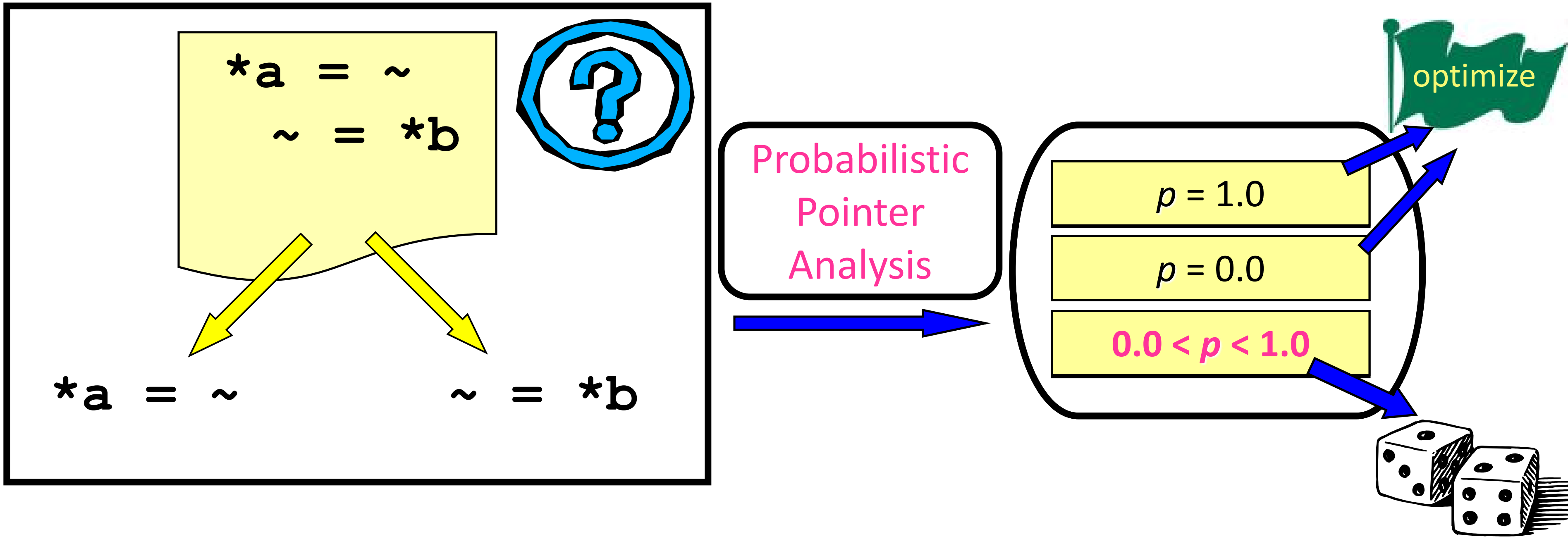
$p = 1.0$

$p = 0.0$

$0.0 < p < 1.0$

- Do pointers `a` and `b` point to the same location?
  - Repeat for every pair of pointers at every program point

Probabilistic Pointer Analysis



`*a = ~`
`~ = *b`

`*a = ~`
`~ = *b`

Probabilistic Pointer Analysis

$p = 1.0$

$p = 0.0$

$0.0 < p < 1.0$

optimize

- Potential advantage of Probabilistic Pointer Analysis:
  - it doesn’t need to be safe

PPA Research Objectives

- Accurate points-to probability information
  - at every static pointer dereference
- Scalable analysis
  - Goal: entire SPEC integer benchmark suite
- Understand scalability/accuracy tradeoff
  - through flexible static memory model

Improve our understanding of programs

Algorithm Design Choices

Fixed:

- Bottom Up / Top Down Approach
- Linear transfer functions (for scalability)
- One-level context and flow sensitive

Flexible:

- Edge profiling (or static prediction)
- Safe (or unsafe)
- Field sensitive (or field insensitive)

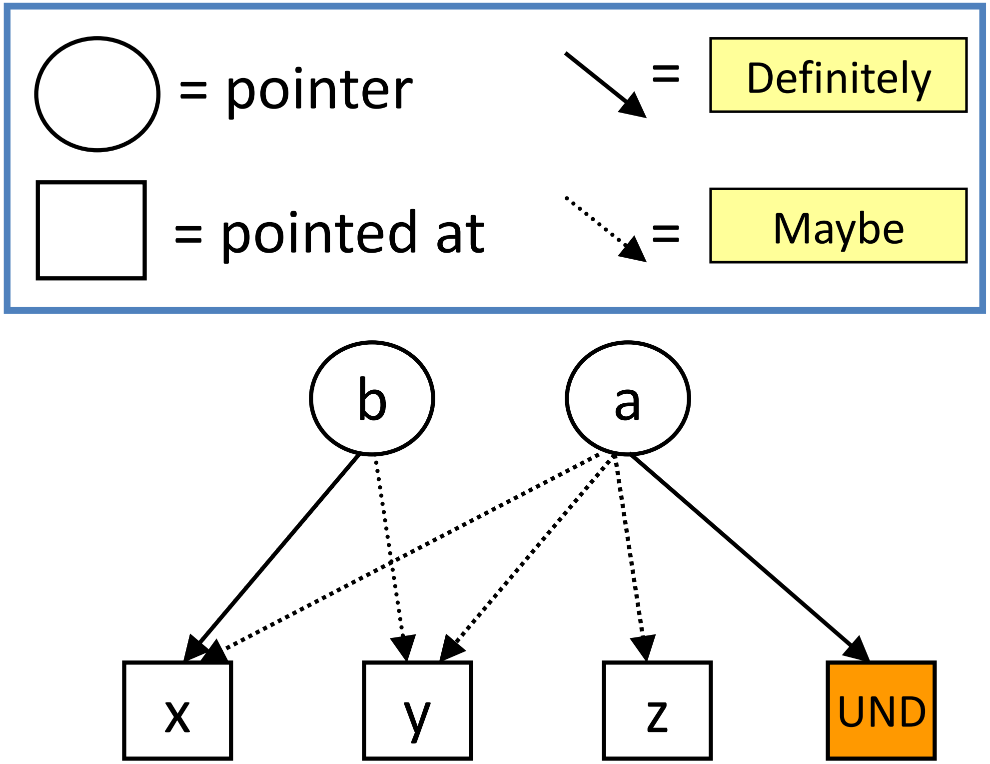
Traditional Points-To Graph

```
int x, y, z, *b = &x;
void foo(int *a) {

  if(…)
    b = &y;

  if(…)
    a = &z;
  else(…)
    a = b;

  while(…) {
    x = *a;
    …
  }
}
```



Results are inconclusive

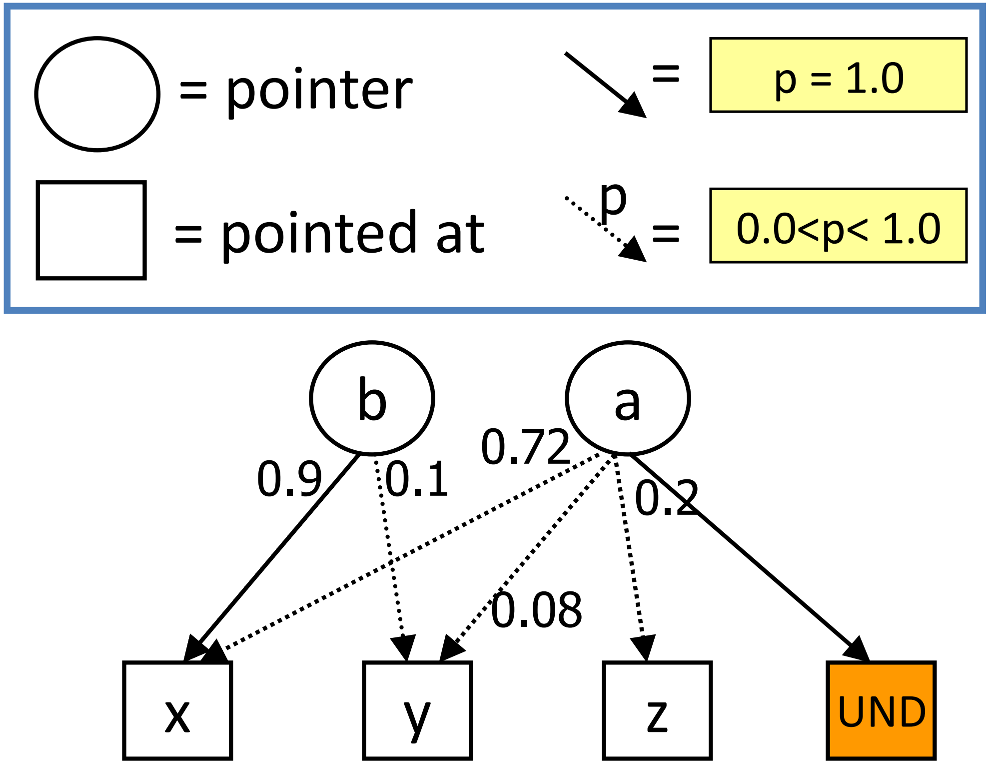
Probabilistic Points-To Graph

```
int x, y, z, *b = &x;
void foo(int *a) {

  if(…)  ⇨0.1 taken(edge profile)
    b = &y;

  if(…)  ⇨0.2 taken(edge profile)
    a = &z;
  else
    a = b;

  while(…) {
    x = *a;
    …
  }
}
```



Results provide more information

Probabilistic Pointer Analysis Results Summary

- Matrix-based, transfer function approach
  - SUIF/Matlab implementation
- Scales to the SPECint 95/2000 benchmarks
  - One-level context and flow sensitive
- As accurate as the most precise algorithms
- Interesting result:
  - ~90% of pointers tend to point to only one thing

Pointer Analysis Summary

- Pointers are hard to understand at compile time!
  - Accurate analyses are large and complex

- Many different options:
  - Representation, heap modeling, aggregate modeling, flow sensitivity, context sensitivity
  - Multi-threaded code

- Many algorithms:
  - Address-taken, Anderson, Steensgarde, etc
  - BDD-based, probabilistic

- Many trade-offs:
  - Space, time, accuracy, safety

Choose the right type of analysis given how the information will be used

Today's Class

- Basics
- Design Options
- Pointer Analysis Algorithms
- Pointer Analysis Using BDDs
- Probabilistic Pointer Analysis

Friday's Class

- Memory Hierarchy Optimization