CSC D70: Compiler Optimization Pointer Analysis

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The content of this lecture is adapted from the lectures of Todd Mowry, Greg Steffan, and Phillip Gibbons

Outline

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

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

Pointer Analysis Basics: Aliases

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

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

Alias Sets ?

{x, *p, *r}

{y, *q, **s}

{q, *s}

p and q point to different locs

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

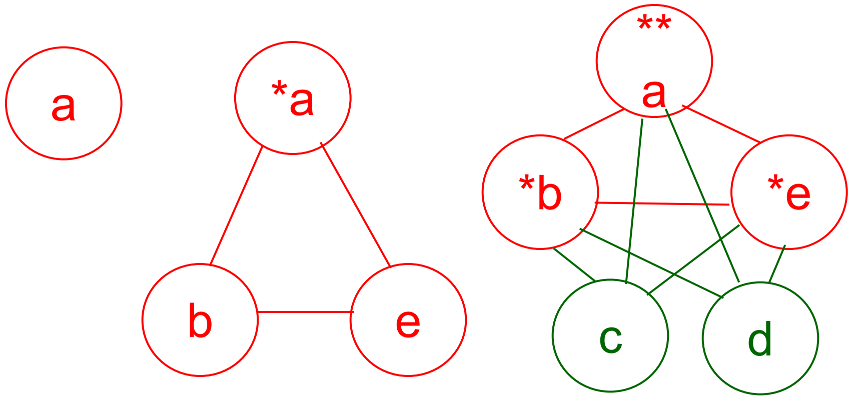
- Complexity: huge in space and time
  - compare every pointer with every other pointer
  - at every program point
  - potentially considering all program paths to that point
- Scalability vs. accuracy trade-off
  - different analyses motivated for different purposes
  - many useful algorithms (adds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

Pointer Analysis: Design Options

- Representation
- Heap modeling
- Aggregate modeling
- Flow sensitivity
- Context sensitivity

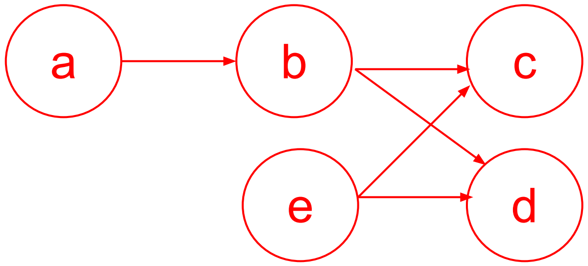
Alias Representation

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



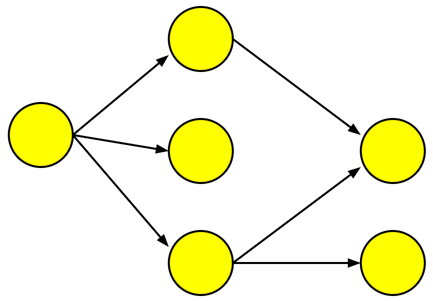
- Track **points-to** info
  - <a, b>, <b, c>, <b, d>,
    <e, c>, <e, d>
  - Less precise, more efficient
  - Why?

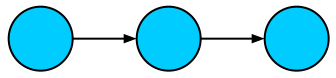
```
a = &b;
b = &c;
b  = &d;
e = b;
```



Heap Modeling Options

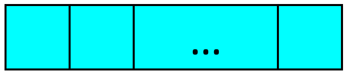
- Heap merged
  - i.e. "no heap modeling"
- Allocation site (any call to malloc/calloc)
  - Consider each to be a unique location
  - Doesn't differentiate between multiple objects allocated by the same allocation site
- Shape analysis
  - Recognize linked lists, trees, DAGs, etc.





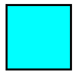
Aggregate Modeling Options

Arrays



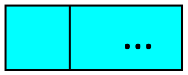
Elements are treated as individual locations

or



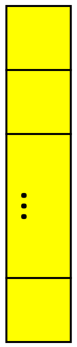
Treat entire array as a single location

or



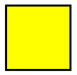
Treat first element separate from others

Structures



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

or



Treat entire structure as a single location

What are the tradeoffs?

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
  - 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

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} ⍰ {heapS1, heapS2, heapS4, heapS6}

(order doesn't matter, union of all possibilities)

Flow Sensitive

a_{S7} ⍰ {heapS2, heapS4, heapS6}

(in-order, doesn't know s5 & s6 are exclusive)

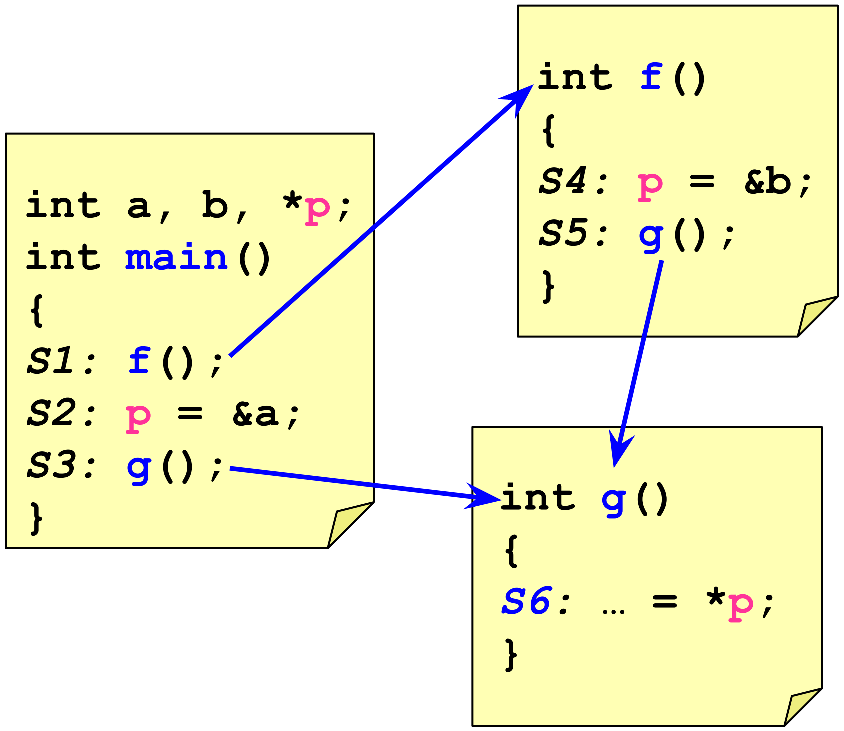
Path Sensitive

a_{S7} ⍰ {heapS2, heapS6}

(in-order, knows s5 & s6 are exclusive)

Context Sensitivity Options

- Context insensitive/sensitive
  - 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} => {a,b}

Context Sensitive:

Called from S5:p_{S6} => {b}
Called from S3:p_{S6} => {a}

Pointer Alias Analysis Algorithms

References:

- *"Points-to analysis in almost linear time"*, Steensgaard, POPL 1996
- *"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
- *"Pointer analysis: haven't we solved this problem yet?"*, Hind, PASTE 2001
- *"Which pointer analysis should I use?"*, Hind et al., ISSTA 2000
- …

- "*Introspective analysis: context-sensitivity, across the board*", Smaragdakiset al., PLDI 2014
- "*Sparse flow-sensitive pointer analysis for multithreaded programs*", Sui et al., CGO 2016
- "*Symbolic range analysis of pointers*", Paisanteet 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} = {heap_S1, p, heap_S4, heap_S6, q, heap_S8, 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

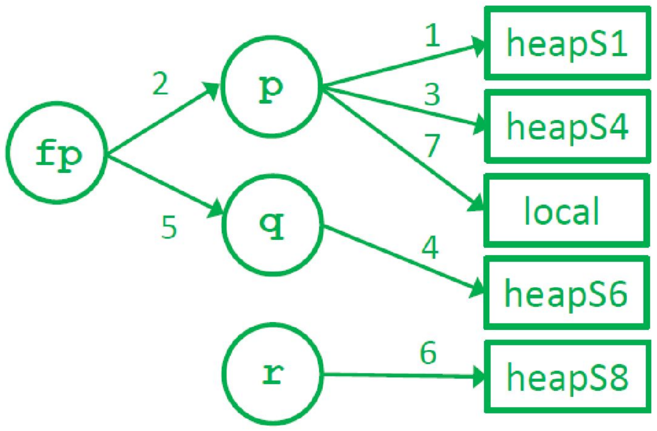
```
T *p, *q, *r;

int main() {
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} = {heap_S1, heap_S4, 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: O(n)
- Precision: less precise than Andersen’s

Steensgaard Example

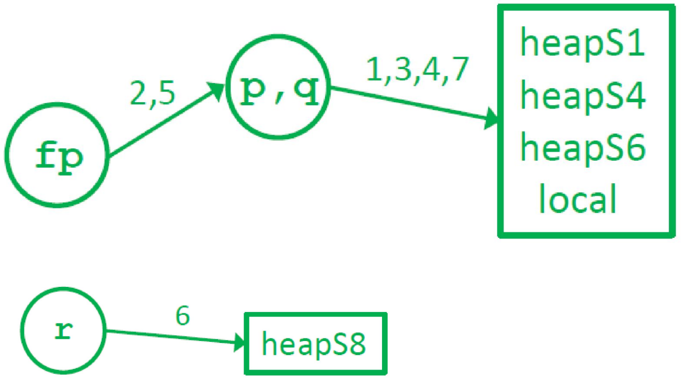
```
T *p, *q, *r;

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} = {heap_S1, heap_S4, heap_S6, 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} = {heap_S4}

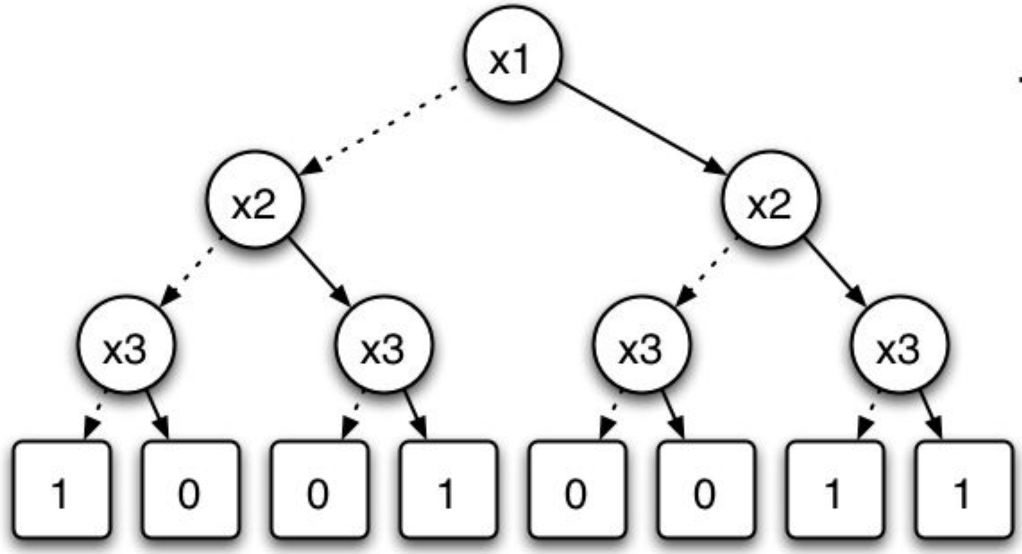
p_{S9} = {local, heap_s1}

Pointer Analysis Using BDDs: Binary Decision Diagrams

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

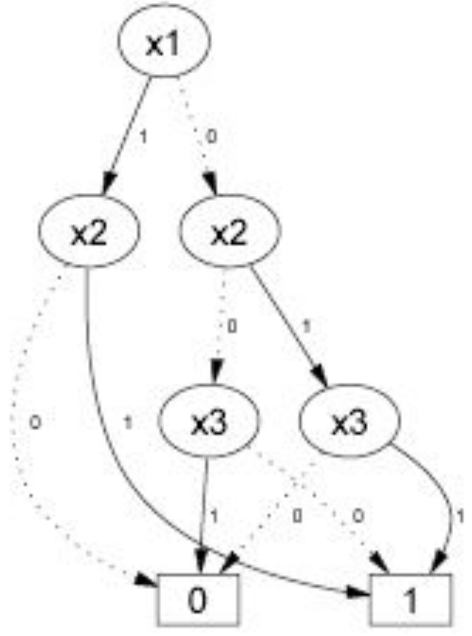
Binary Decision Diagram (BDD)



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

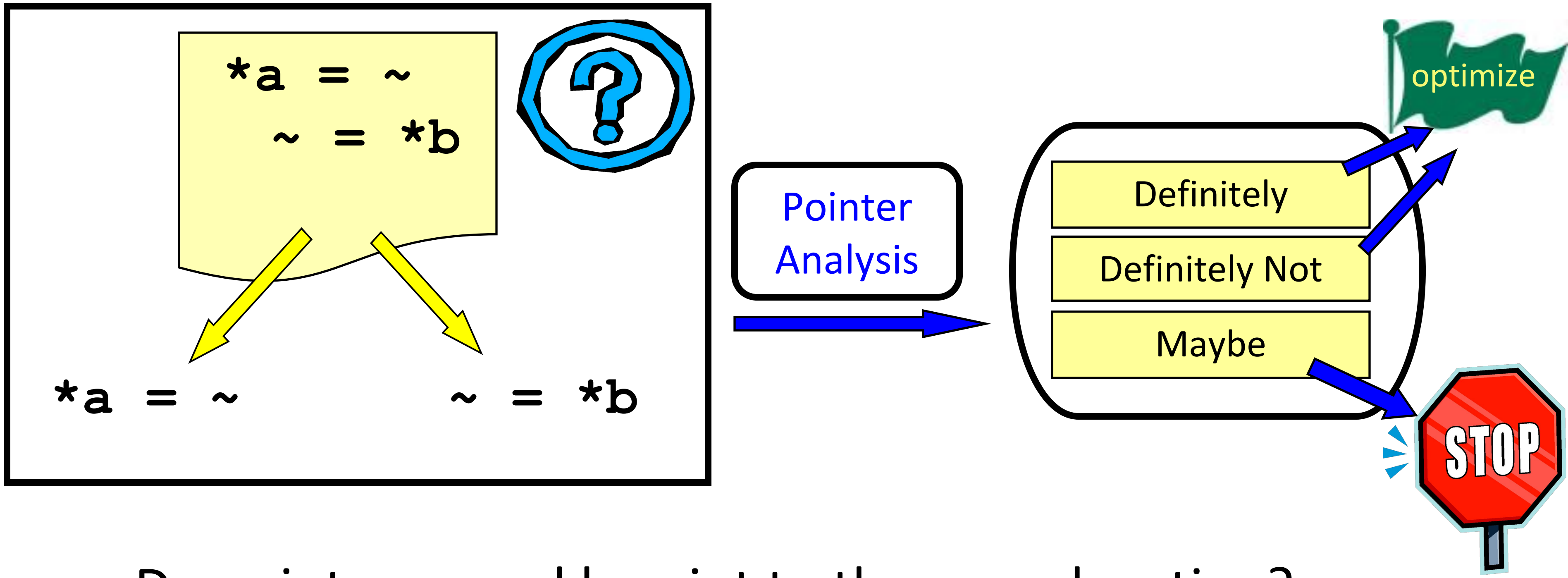
- Use a BDD to represent transfer functions
  - encode procedure as a function of its calling context
  - compact and efficient representation
- Perform context-sensitive, inter-procedural analysis
  - similar to dataflow analysis
  - but across the procedure call graph
- Gives accurate results
  - and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

Probabilistic Pointer Analysis

<u>References</u>:

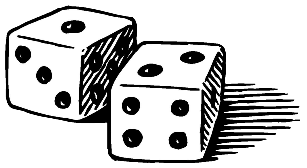
- *"A Probabilistic Pointer Analysis for Speculative Optimizations"*, DaSilva and Steffan, ASPLOS 2006
- *"Compiler support for speculative multithreading architecture with probabilistic points-to analysis"*, Shen et al., PPoPP 2003
- *"Speculative Alias Analysis for Executable Code"*, Fernandez and 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



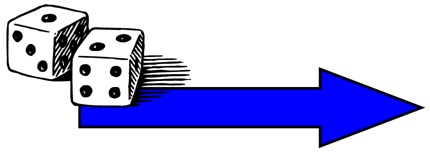
- Do pointers a and b point to the same location?
  - Repeat for every pair of pointers at every program point
- How can we optimize the "maybe" cases?

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?>
```

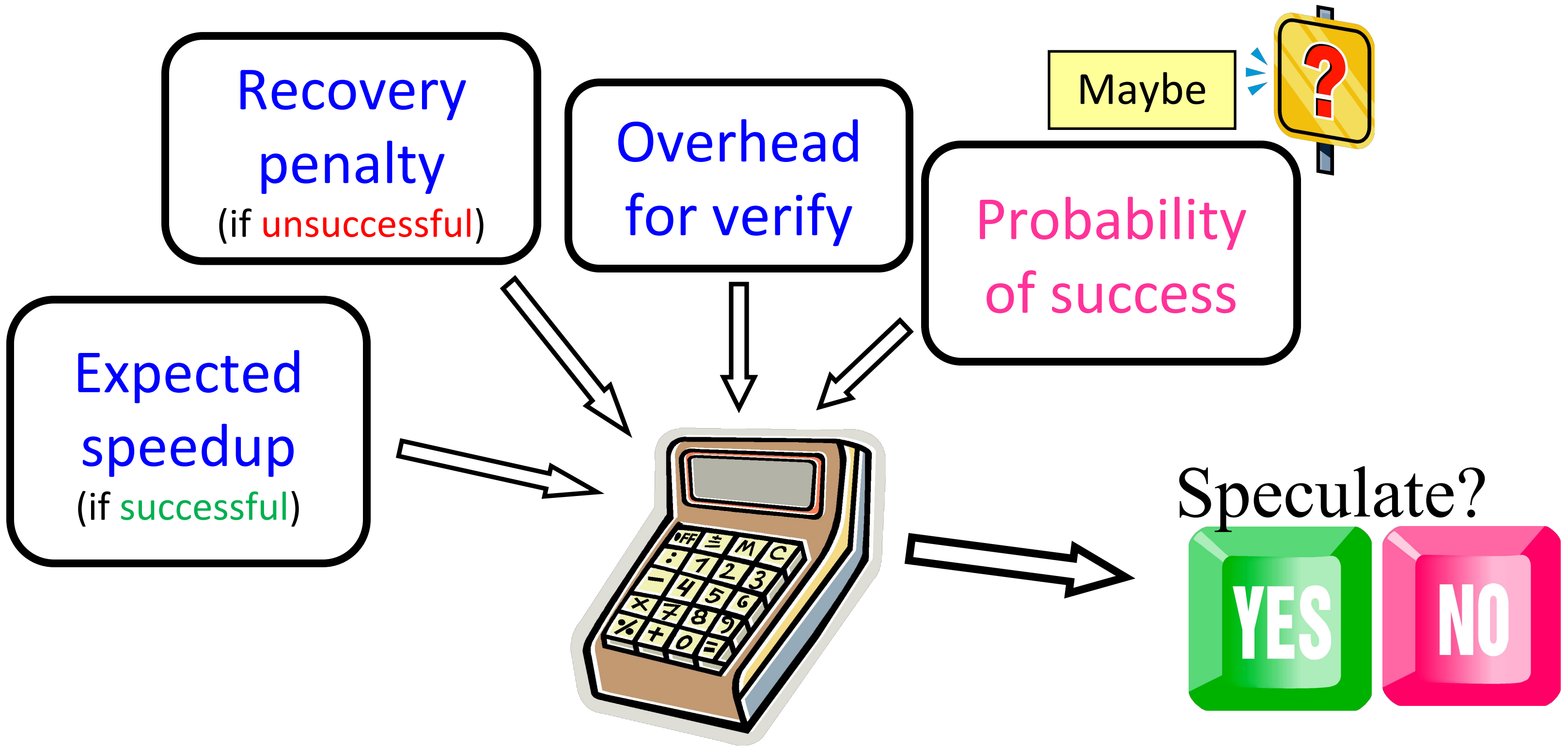
Data Speculative Optimizations

- 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

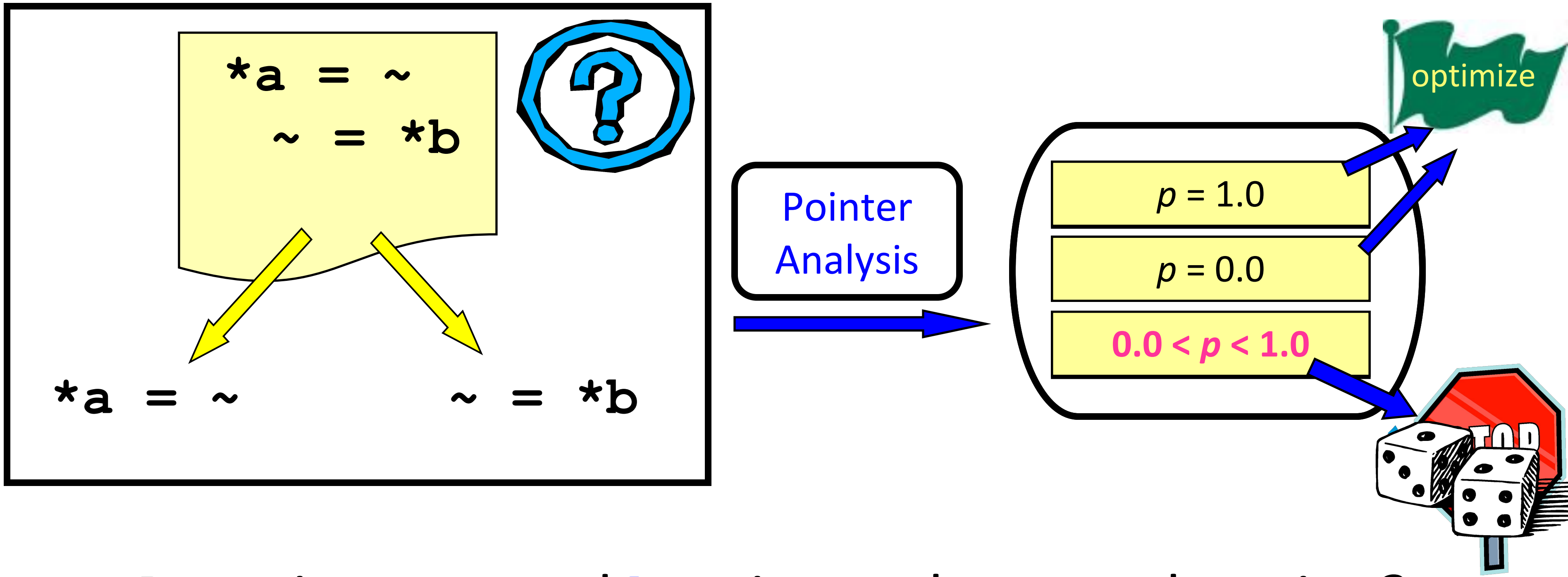
Can We Quantify "Maybe"?

- Estimate the potential benefit for speculating:


Recovery penalty (if unsuccessful)
Overhead for verify
Maybe
Probability of success
Expected speedup (if successful)
Speculate?
YES
NO

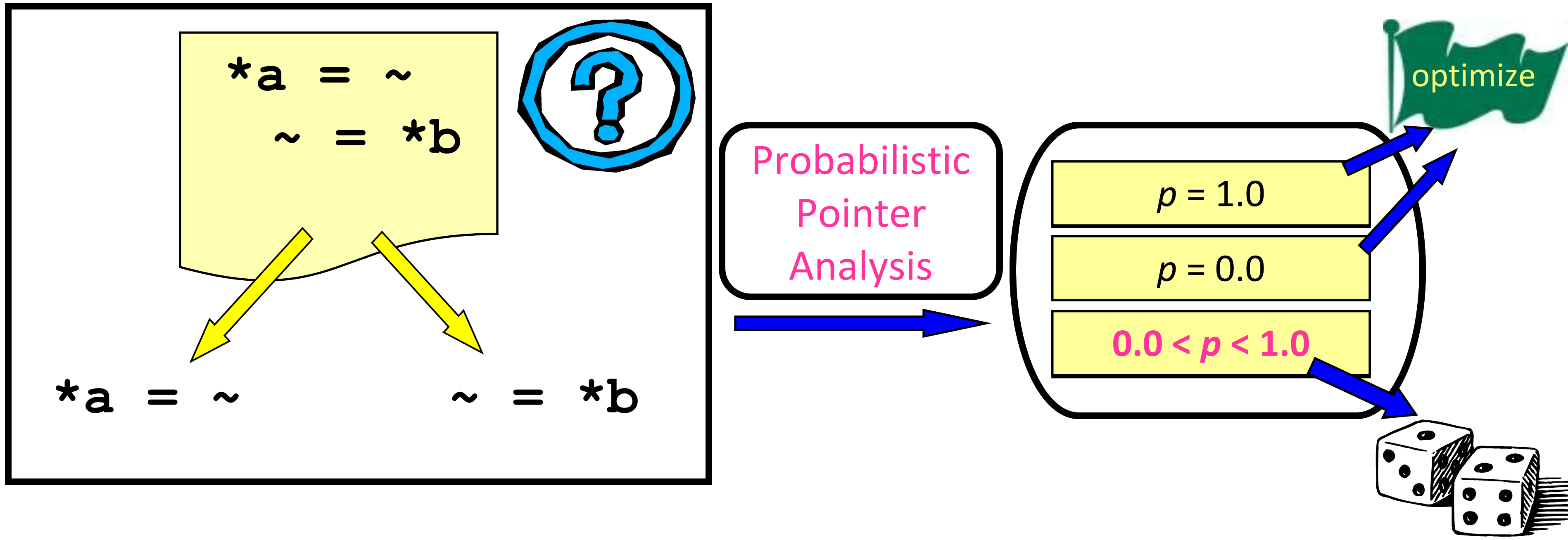
Ideally "maybe" should be a probability.

Conventional Pointer Analysis



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

Probabilistic Pointer Analysis



- 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)

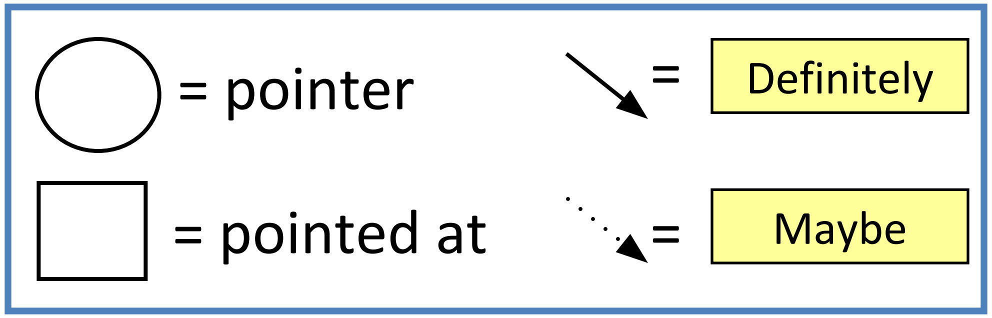
Traditional Points-To Graph

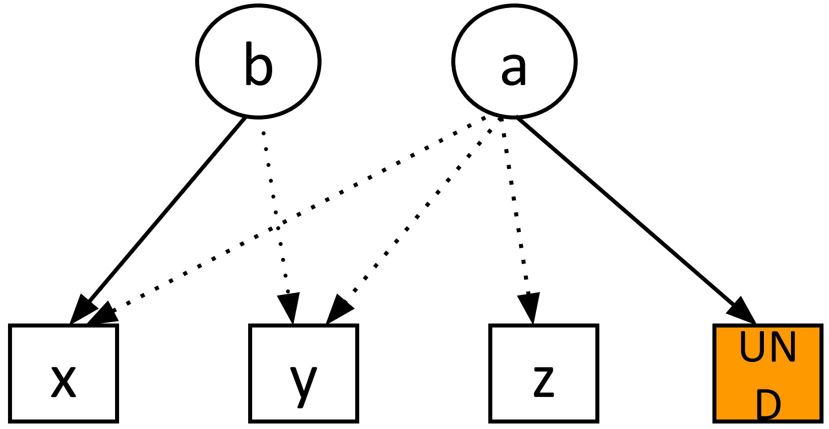
```
int x, y, z, *b = &x;
void foo(int *a) {

   if(…)
      b = &y;

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

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





Results are inconclusive

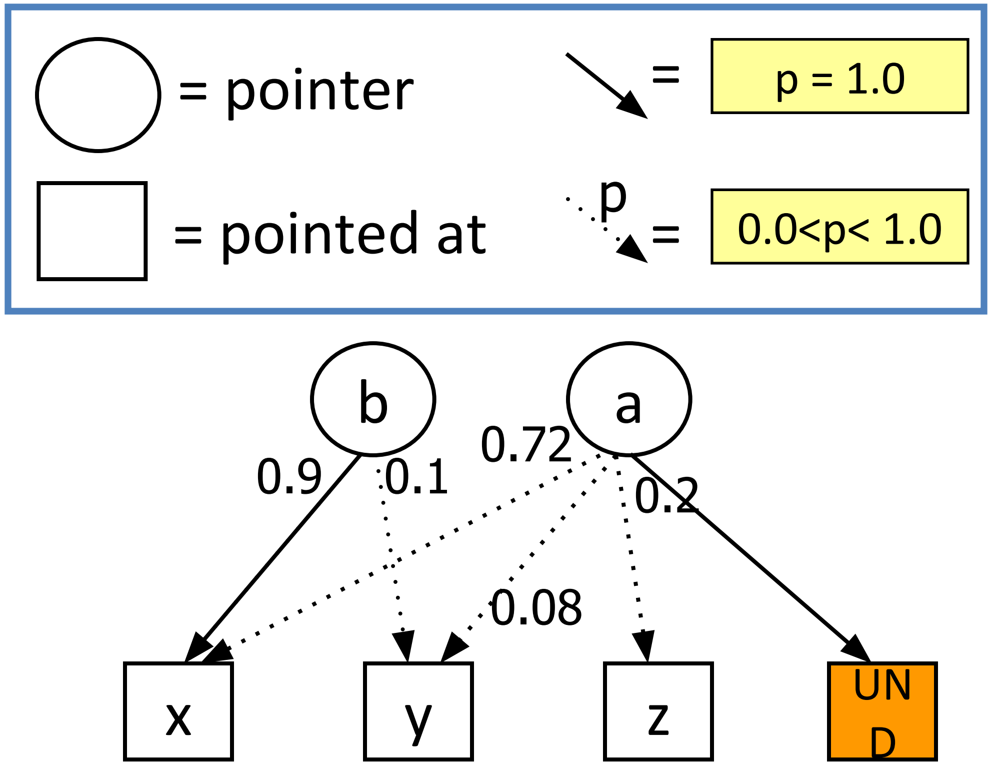
Probabilistic Points-To Graph

```
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
- Many algorithms:
  - Address-taken, Steensgarde, Andersen, Emami
  - BDD-based, probabilistic
- Many trade-offs:
  - space, time, accuracy, safety
- Choose the right type of analysis given how the information will be used

CSC D70: Compiler Optimization Memory Optimizations (Intro)

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University of Toronto

Winter 2019

The content of this lecture is adapted from the lectures of Todd Mowry and Phillip Gibbons

Caches: A Quick Review

- How do they work?
- Why do we care about them?
- What are typical configurations today?
- What are some important cache parameters that will affect performance?

Optimizing Cache Performance

- Things to enhance:
  - temporal locality
  - spatial locality

- Things to minimize:
  - conflicts (i.e. bad replacement decisions)

What can the *compiler* do to help?

Two Things We Can Manipulate

- Time:
  - When is an object accessed?

- Space:
  - Where does an object exist in the address space?

How do we exploit these two levers?

Time: Reordering Computation

- What makes it difficult to know *when* an object is accessed?
- How can we predict a better time to access it?
  - What information is needed?
- How do we know that this would be safe?

Space: Changing Data Layout

- What do we know about an object's location?
  - scalars, structures, pointer-based data structures, arrays, code, etc.
- How can we tell what a better layout would be?
  - how many can we create?
- To what extent can we safely alter the layout?

Types of Objects to Consider

- Scalars
- Structures & Pointers
- Arrays

Scalars

- Locals
- Globals
- Procedure arguments
- Is cache performance a concern here?
- If so, what can be done?

```
int x;
double y;
foo(int a){
   int i;
   …
   x = a*i;
   …
}
```

Structures and Pointers

- What can we do here?
  - within a node
  - across nodes

```
struct {
    int count;
    double velocity;
    double inertia;
    struct node *neighbors[N];
} node;
```

- What limits the compiler's ability to optimize here?

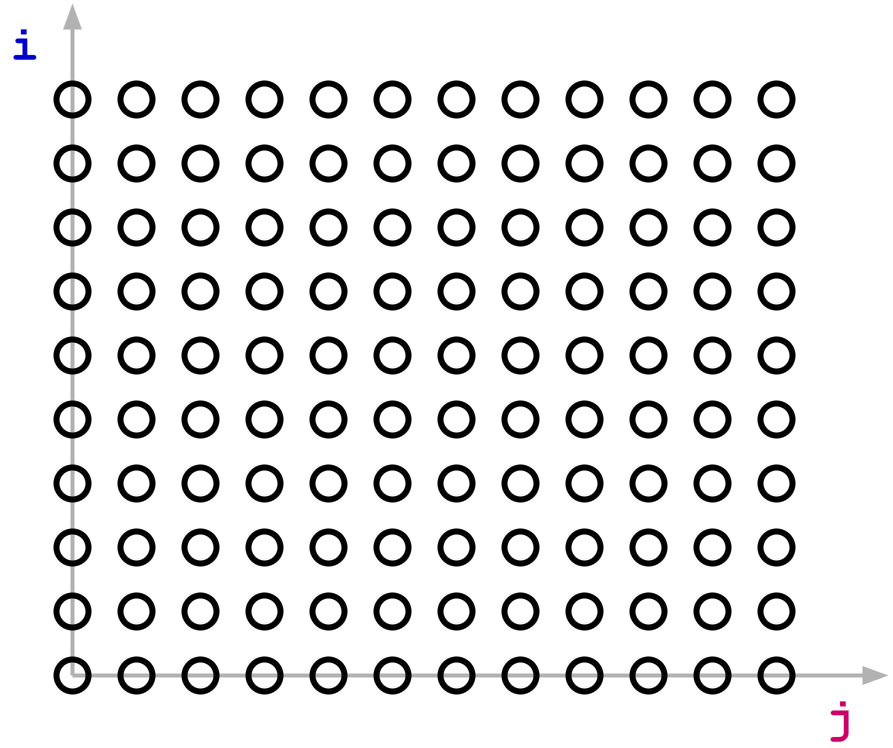
Arrays

```
double A[N][N], B[N][N];
…
for i = 0 to N-1
    for j = 0 to N-1
        A[i][j] = B[j][i];
```

- usually accessed within loops nests
  - makes it easy to understand “time”
- what we know about array element addresses:
  - start of array?
  - relative position within array

Handy Representation: "Iteration Space"

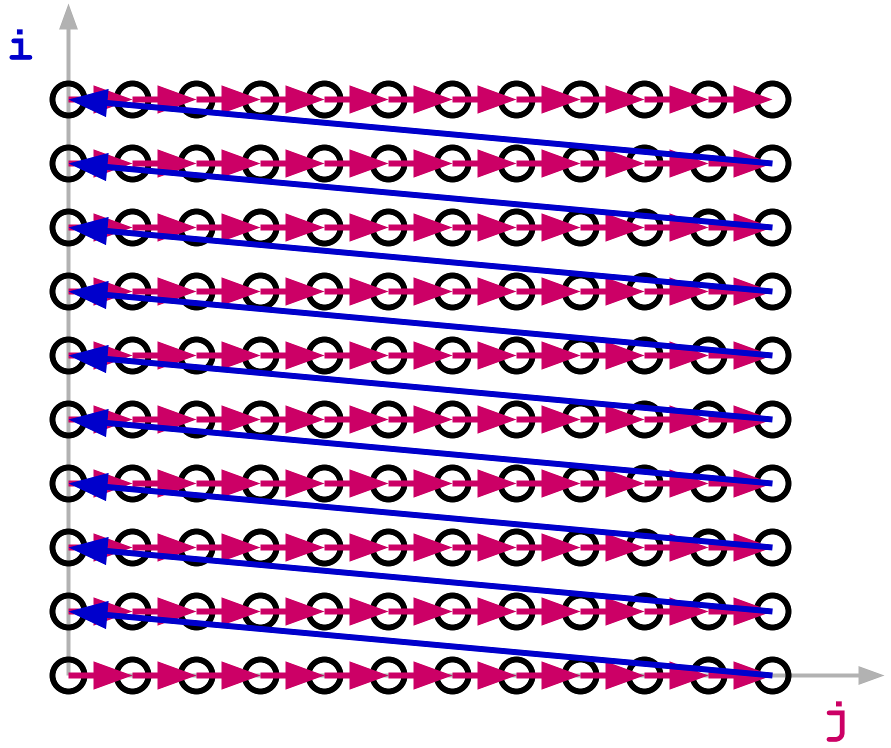
```
for i = 0 to N-1
    for j = 0 to N-1
        A[i][j] =
B[j][i];
```



- each position represents an iteration

Visitation Order in Iteration Space

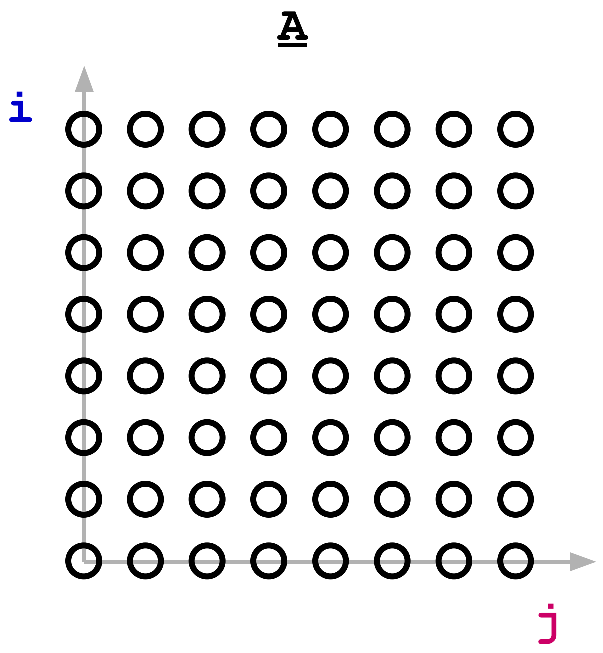
```
for i = 0 to N-1
    for j = 0 to N-1
        A[i][j] =
B[j][i];
```

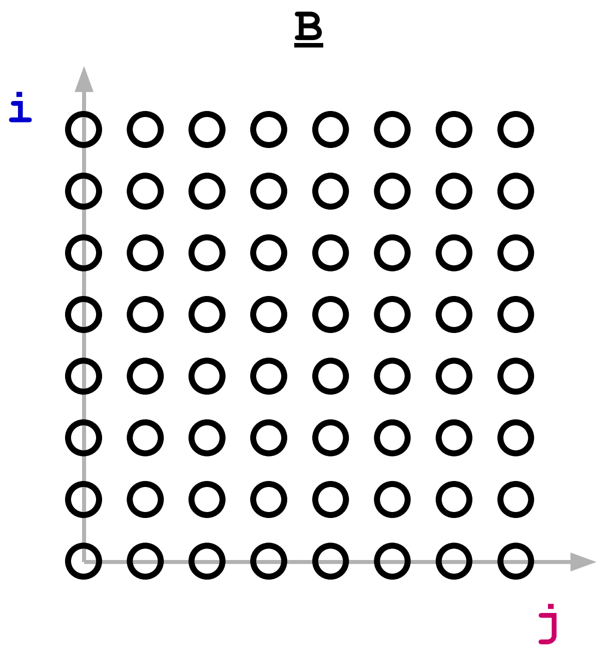


- Note: iteration space ≠ data space

When Do Cache Misses Occur?

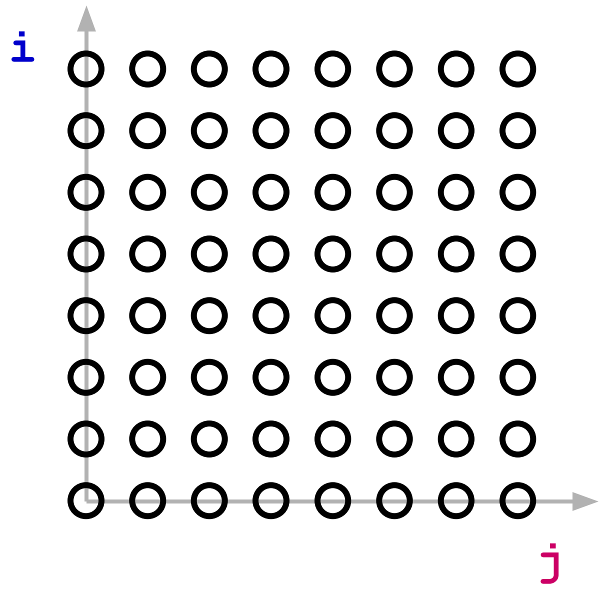
```
for i = 0 to N-1
    for j = 0 to N-1
        A[i][j] = B[j][i];
```





When Do Cache Misses Occur?

```
for i = 0 to N-1
    for j = 0 to N-1
        A[i+j][0] = i*j;
```



Optimizing the Cache Behavior of Array Accesses

- We need to answer the following questions:
  - when do cache misses occur?
    - use “locality analysis”
  - can we change the order of the iterations (or possibly data layout) to produce better behavior?
    - evaluate the cost of various alternatives
  - does the new ordering/layout still produce correct results?
    - use “dependence analysis”

Examples of Loop Transformations

- Loop Interchange
- Cache Blocking
- Skewing
- Loop Reversal
- …

(we will briefly discuss the first two next week)

CSC D70: Compiler Optimization Pointer Analysis & Memory Optimizations (Intro)

Prof. Gennady Pekhimenko
University of Toronto

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The content of this lecture is adapted from the lectures of Todd Mowry and Phillip Gibbons