Pointer Analysis:
Haven't We Solved This Problem Yet?

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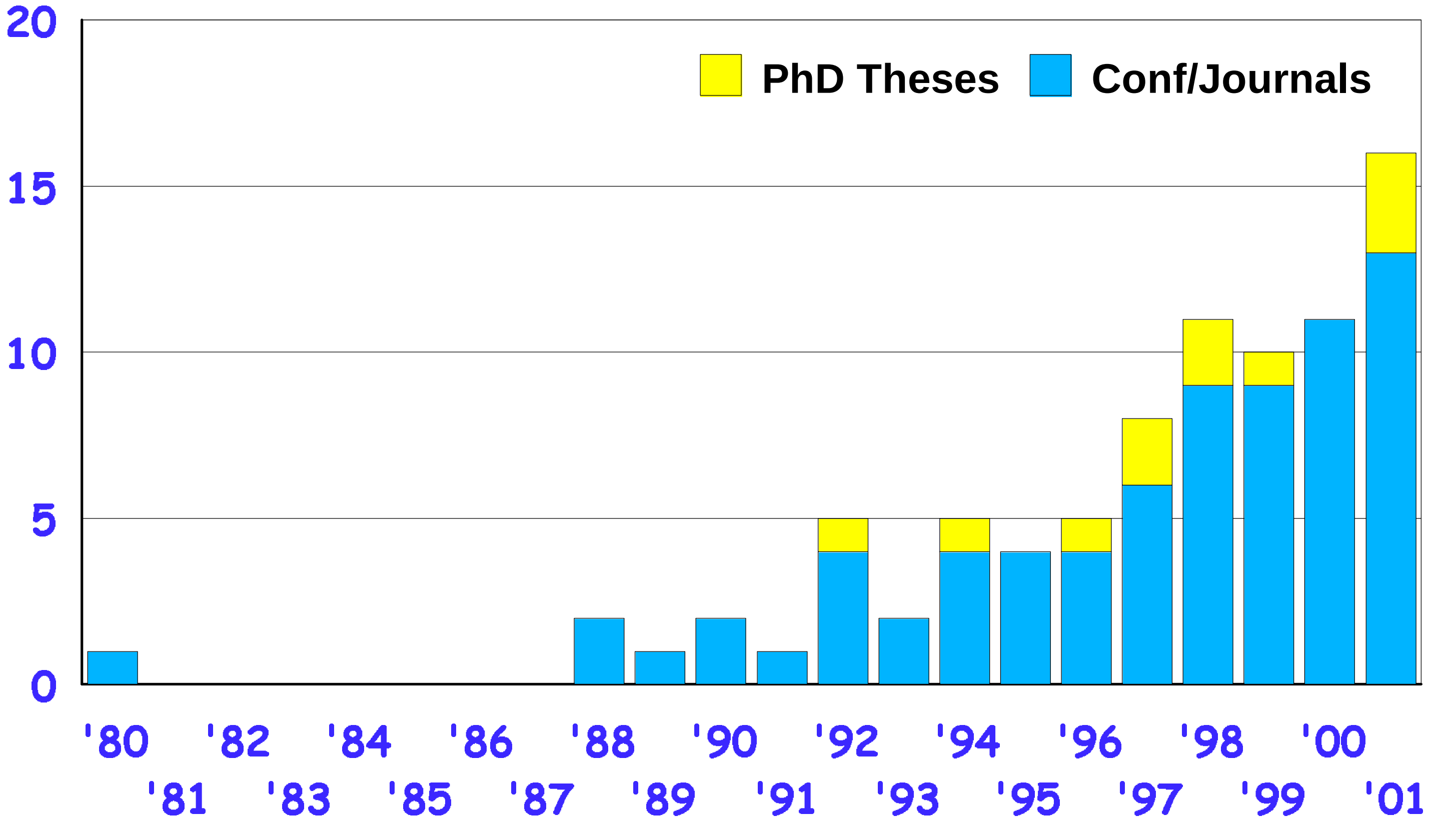
Pointer Analysis Pubs by Year



83 Publications in 14 years!

48 in the last 4 years!

Why should I care?

- needed for any "mod/ref" analysis
  - slicing, dep graph, constant prop, code motion, ...
  - call graph construction
    - needed for any whole program analysis

```
p->data =
          = q->data;
```

```
x = 0;
*p=17;
    = x + ...
```

```
for (. . . ) {
   . . .
   p->data = 0;
}
```

```
(*p)(a, b, c);
q->foo();
```

OK, I need a pointer analysis, which one should I use?

- It depends ...
- Do you want
  - high precision?
  - high efficiency?
  - not a simple question

- Sit back and relax for the next 45 mins

Talk Roadmap

- Ptr Analysis Dimensions
- Metrics
- Survey of Issues
- Conclusions

Feature:

input from several ptr analysis experts

Pointer Analysis

Goal: statically determine what can be accessed by a pointer

Bad news: problem is undecidable

Good news: many approximation algorithms exist!

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Bad news: problem is undecidable

Bad news: many approximation algorithms exist!

Worst case complexities:
linear ... doubly exponential

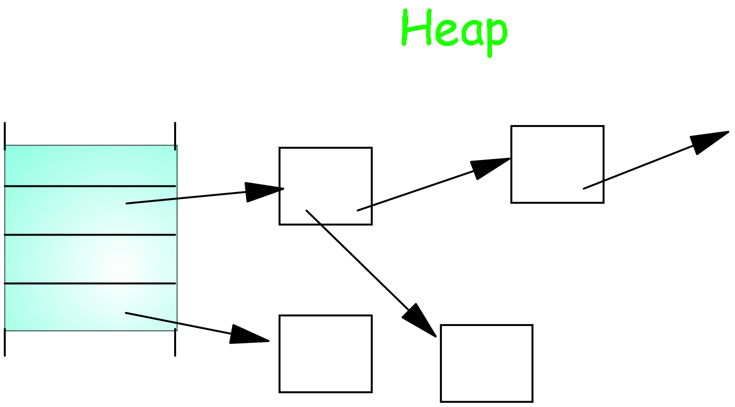
Is "Big-$\mathcal{O}$" the same as "Big Ben"?

Pointer Analysis Dimensions

- Flow sensitivity
- Context sensitivity
- Heap modeling
- Aggregate modeling
- Alias representation
- Whole program

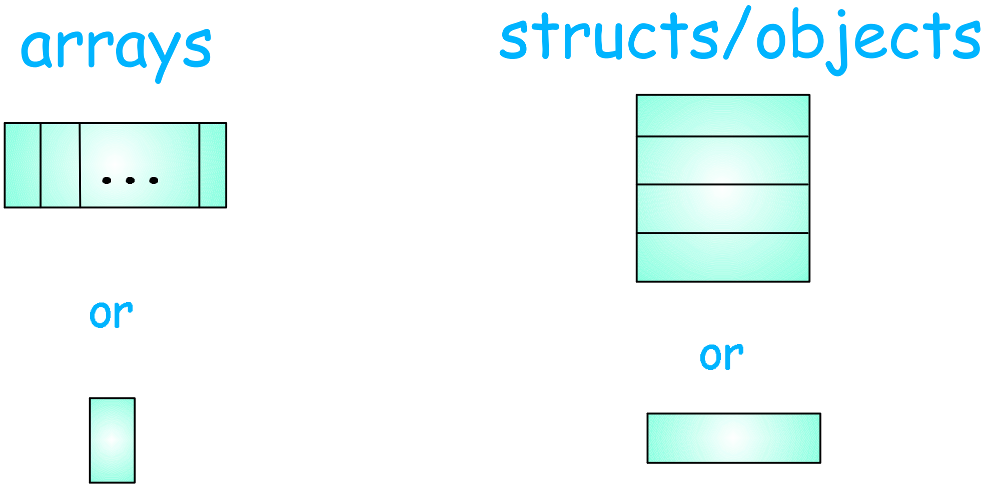
Pointer Analysis Dimensions

- Heap modeling
  - allocation site
  - connection analysis
  - shape analysis



Pointer Analysis Dimensions

- Heap modeling
- Aggregate modeling



arrays

or

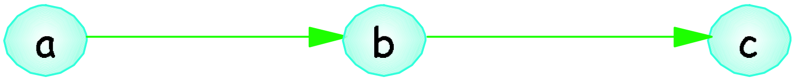
structs/objects

or

Pointer Analysis Dimensions

- Heap modeling
- Aggregate modeling

- Alias representation
  - points-to relations vs explicit alias representations



points-to

<a, b>

<b, c>

explicit alias rep

<*a,b>, <**a, c>

<*b, c>, <**a, *b>

Precision/efficiency tradeoffs exist [HBCC99,RLSZA01], but have not been studied!

Pointer Analysis Dimensions

- Heap modeling
- Aggregate modeling
- Alias representation

- Requires whole program?

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- Requires whole program?

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  - considers control flow during the analysis
  - Flow-sensitive
    - one solution/program point
    - more precise, less efficient (time and space)

Pointer Analysis Dimensions

- Heap modeling
- Aggregate modeling
- Alias representation
- Requires whole program?

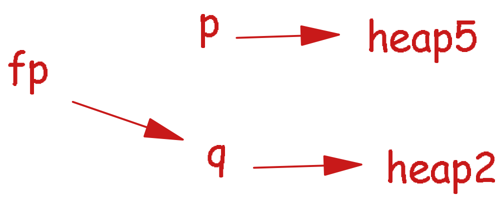
- Flow-sensitivity
  - considers control flow during the analysis
  - Flow-sensitive
    - one solution/program point
    - more precise, less efficient (time and space)
  - Flow-insensitive
    - one solution/whole program or function
    - less precise, more efficient
    - equality-based (almost linear)
    - subset-based (polynomial)

Example

```
1:  p = malloc();
2: q = malloc();
3: fp = &p;
4: fp = &q;
5: p = malloc();
6:  ... = *p;
```

Points-to Relations at 6

Flow-sensitive analysis



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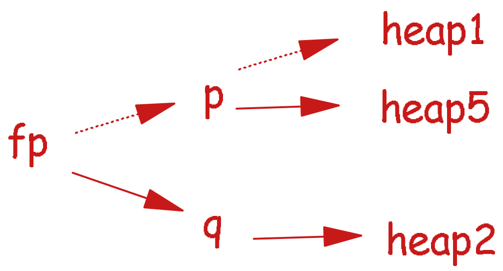
Points-to Relations (at 6)

Subset-based flow-insensitive



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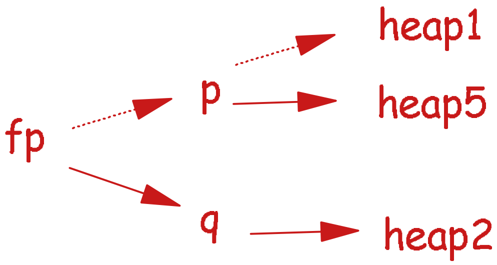
Points-to Relations (at 6)

Equality-based flow-insensitive



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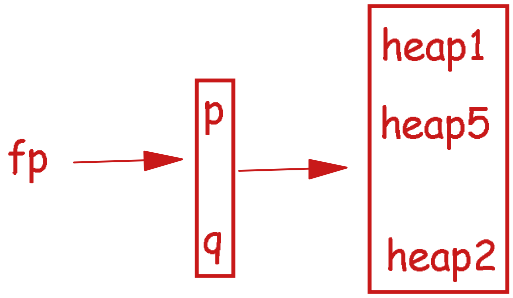
Points-to Relations (at 6)

Equality-based flow-insensitive



Example

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Aliases of *p at 6:

Flow-sensitve: heap5

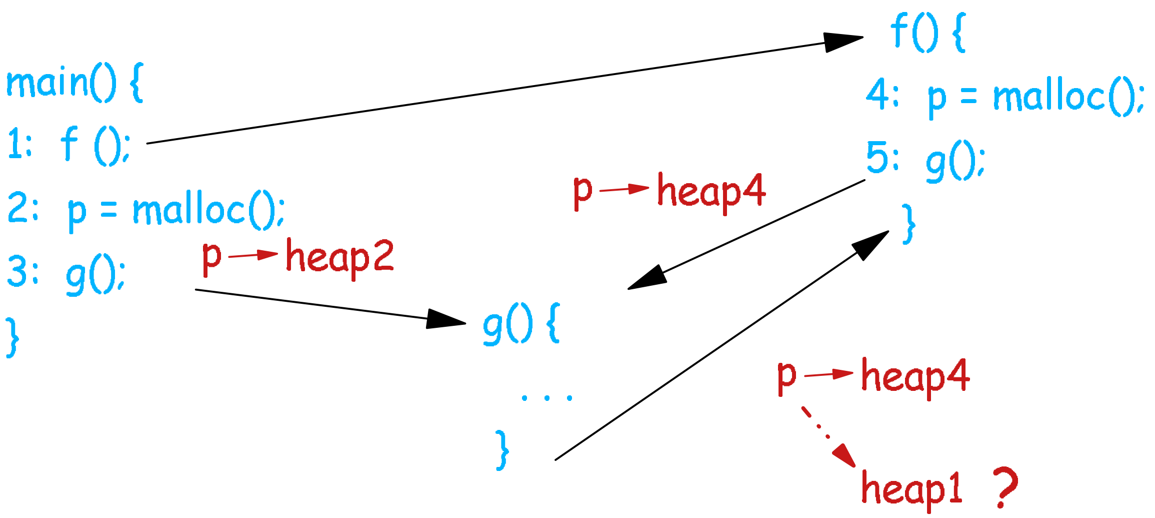
FI subset: heap5 heap1

FI equality: heap5, heap1, heap2

Pointer Analysis Dimensions

- Heap modeling
- Aggregate modeling
- Alias representation
- Requires whole program?
- Flow sensitivity
- Context sensitivity

  Is calling context considered when processing a method?



```
main() {
1:  f ();
2:  p = malloc();
3:  g();
}
```

```
f() {
4:  p = malloc();
5:  g();
}
```

```
g() {
  . . .
}
```

p → heap2

p → heap4

p → heap4

heap1 ?

Talk Roadmap

- Ptr Analysis Dimensions
- **Metrics**
- Survey of Issues
- Conclusions

Metrics

Direct method: avg num objects at ptr deref

- Most popular
- Advantages
  - easy to understand
- Disadvantages
  - no inherent meaning
  - dependence on heap/recursive local model
  - client analyses

Metrics

- Direct method

- Pct of worst-case
  - not popular
  - incorporates language semantics

Metrics

- Direct method
- Worst-case

- Client impact
  - Adv: can see impact on client
  - Dis: only reports on one client

Metrics

- Direct method
- Worst-case
- Client impact

- Dynamic metric
  - direct method
  - client impact
  - Adv: gives lower bound
  - Dis: limited to one run, is lower bound tight?

Metrics

- Direct method
- Worst-case
- Client impact
- Dynamic metric

Recommendation: use combinations [DMM97]

Reproducible Results

- Given dimensions, many experiments are possible
- Often not performed, less often repeated
- Will it be published?
- Can be difficult because of
  - different intermediate representations
  - benchmark suites
  - benchmark versions
- Sharing infrastructure, benchmarks is crucial
- Isn't this at the heart of being a "science"?

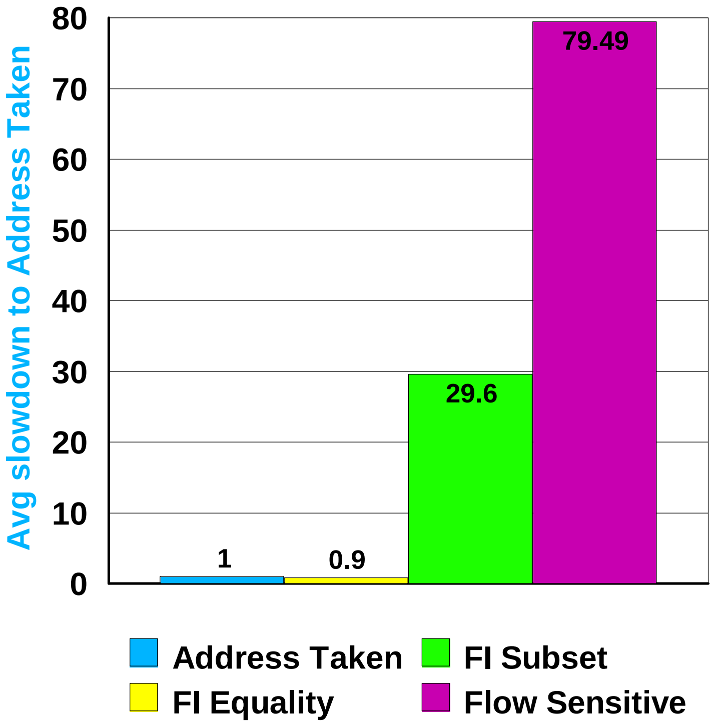
Precision/Scalability

- Equality-based can analyze 1 MLOC
  - getting more precise [LH99, D00]
- Subset-based more precise, but haven't scaled well
  - but, getting more efficient!
    [FFSA98,SFA00,RC00,FRD00,RF01,HT01]
- Convergence may provide the answer, but ...
  is subset-based precision sufficient for all clients?
- More precise/expensive ptr analysis can make clients more efficient [SH97, HP00]

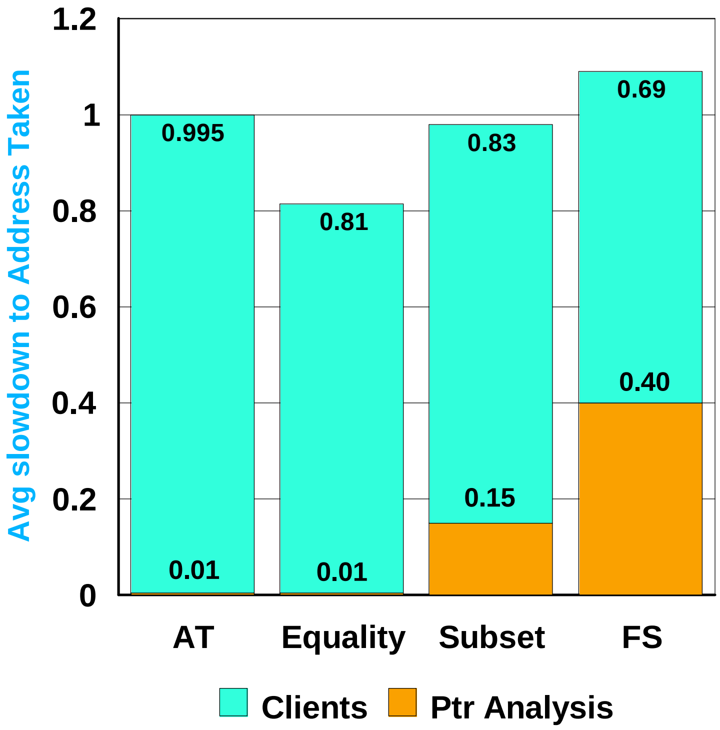
Efficiency (Time)

[HP00]

Pointer Analysis Only

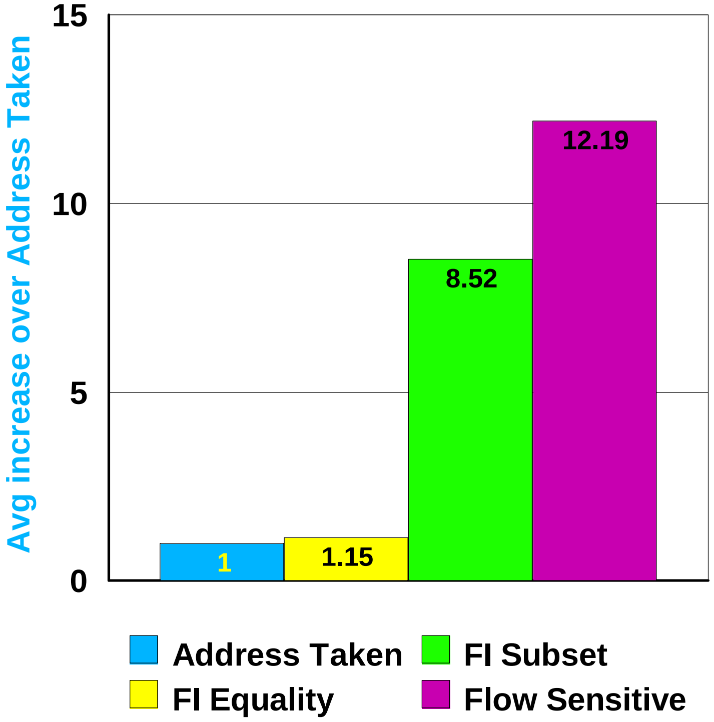


Ptr + All Client Analyses

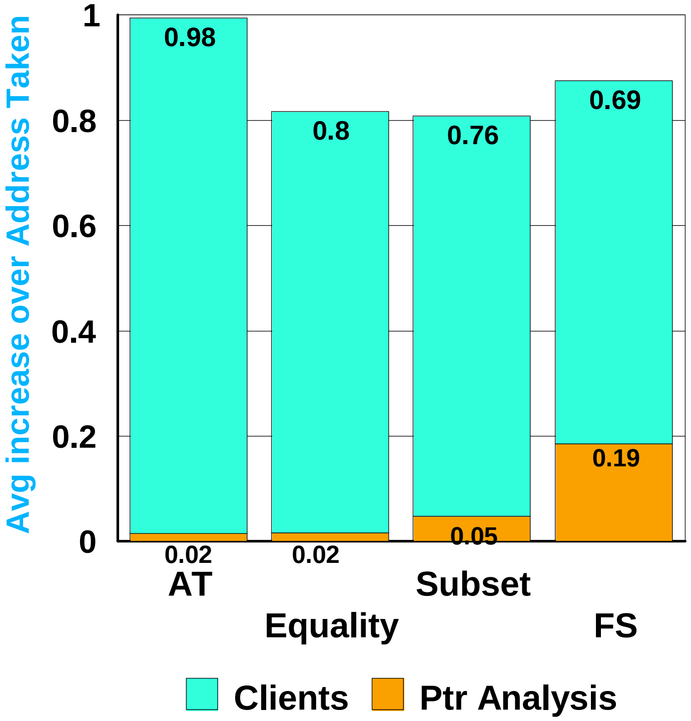


Efficiency (Memory)

Pointer Analysis Only



Ptr + All Client Analyses



Precision/Scalability

``It is easy to make a pointer analysis that is very fast and scales to large programs. But are the results worth anything? While more people have done work in the area, we still need a better understanding of what pointer analysis one should use.''

Amer Diwan

Precision/Scalability

- Bill Landi:
  - relaxing safety
  - Flow and context-sensitive analysis
    - days to minutes
    - false positives/negatives are a problem, maybe?
  - users: false positives => poorly written code

- Susan Horwitz:
  - determine part of program (code region, ptr variable, etc.) that needs high accuracy
  - find special cases where analysis works well, even if it is not general.

Satisfying the Client

- Precision/efficiency required depends on client
- Barbara Ryder:
  - should look for classes of clients with similar needs

- Manuel Fahndrich:
  - two such clients
    - optimizations
      - current analyses may be sufficient
    - error detection & program understanding tools
      - lower bound on precision

- Manuvir Das:
  - error detection => Killer App for pointer analysis

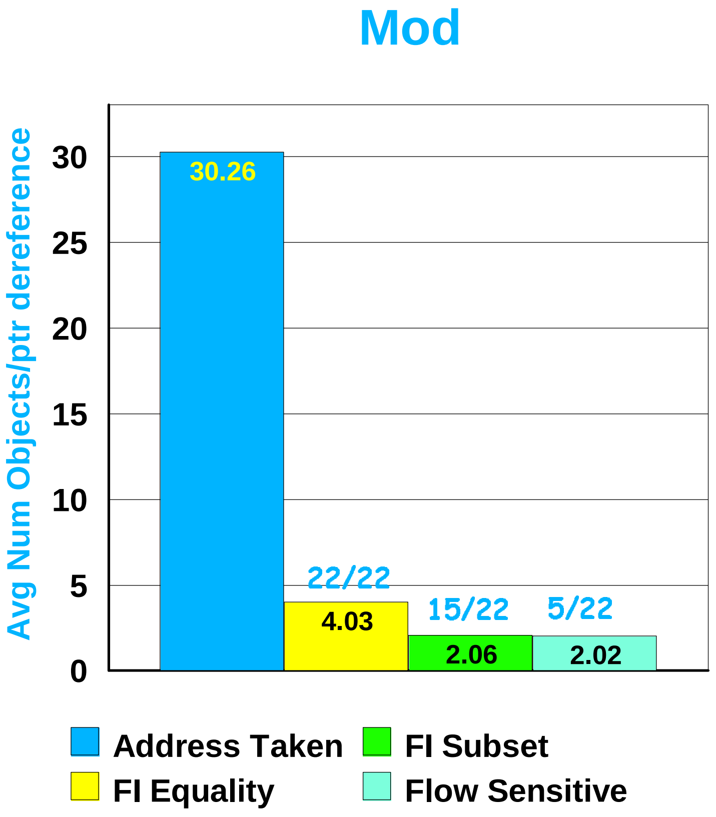
Does Flow-Sensitivity Matter?

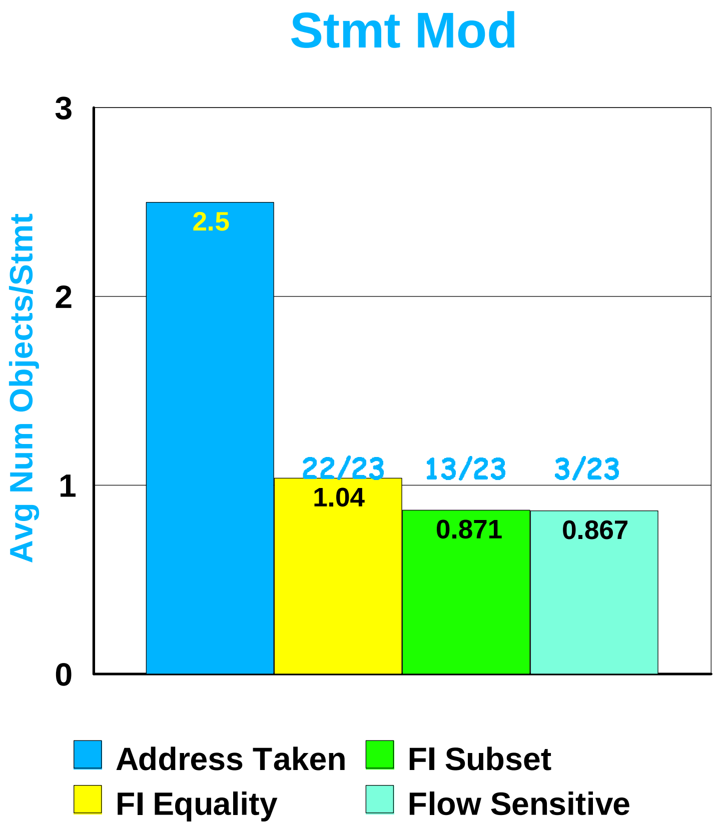
- Flow-sensitive analysis does not provide significant precision improvement over subset-based flow-insensitive [HP00]
  - Assuming:
    no CS, malloc site, pts-to, whole program, aggregates summarized

- Need more studies, clients

Direct Precision

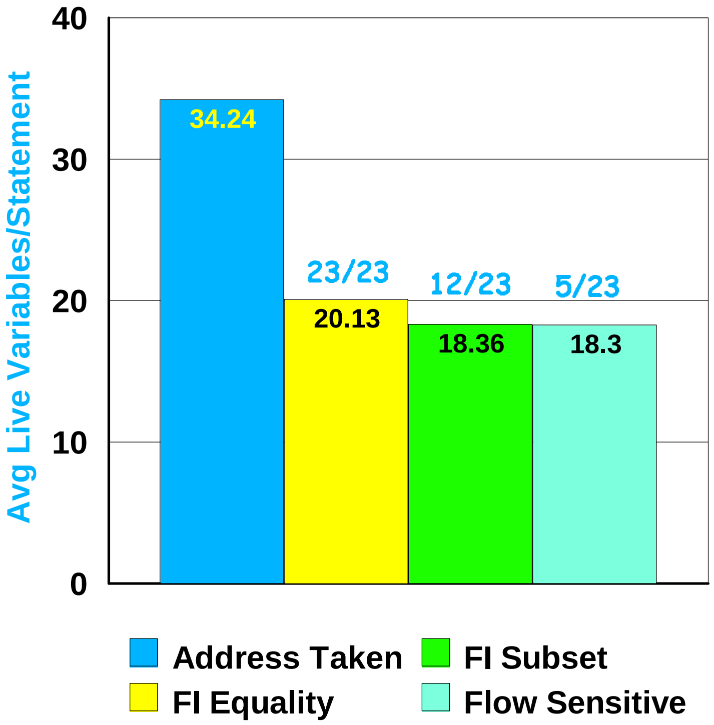
[HP00]


Mod

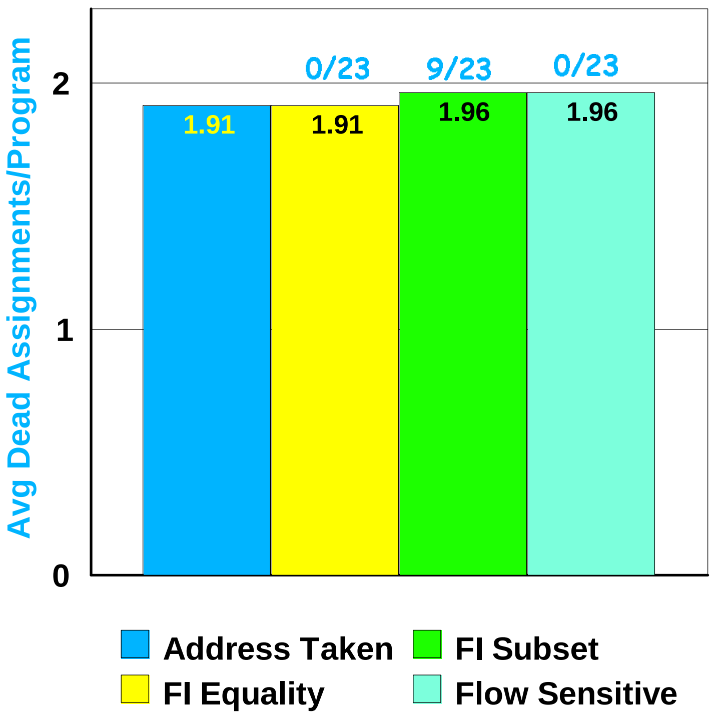

Stmt Mod

Live Variables and Dead Assignments

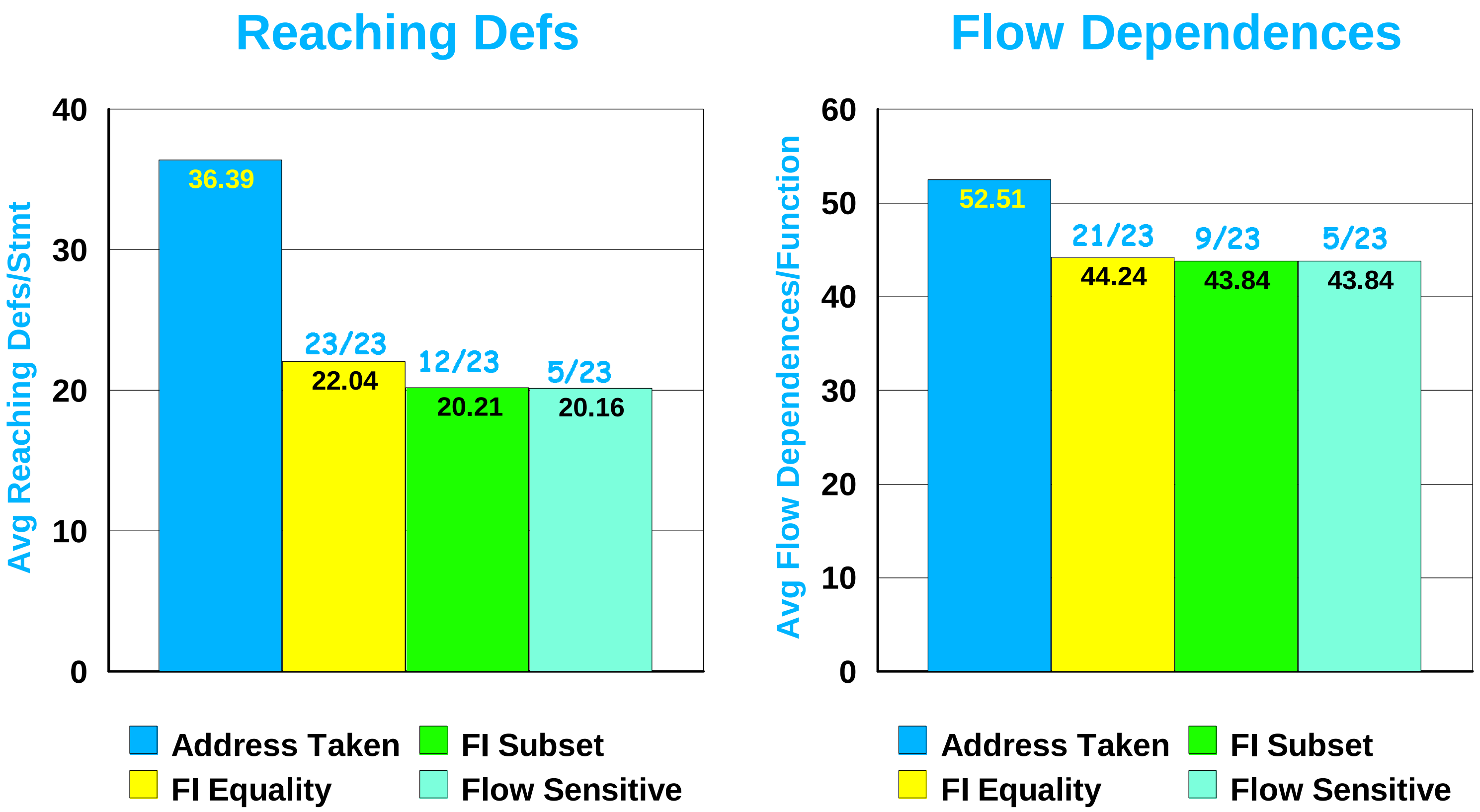
Live Variables



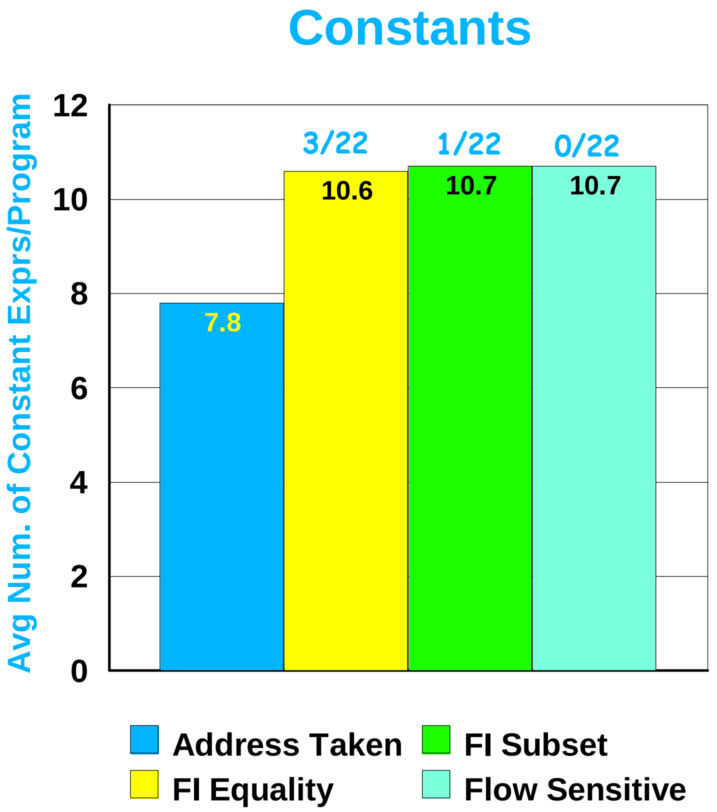
Dead Assignments

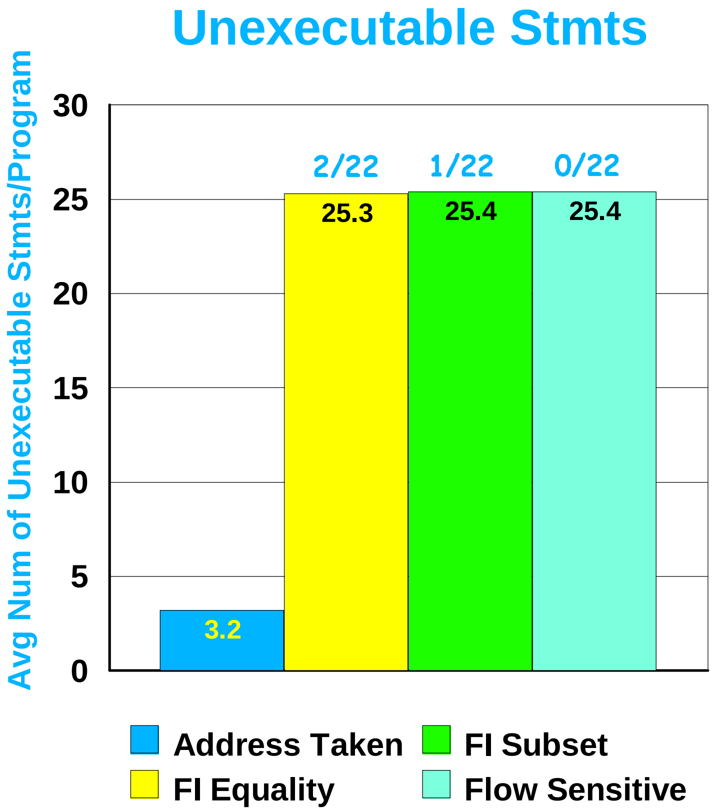


Reaching Defs and Flow Dependences



Constant Propagation and Unexecutable Stmts


Constants


Unexecutable Stmts

Does Context-Sensitivity Matter?

- Exponential worst-case => improving efficiency [EGH94,WL95]
- Does it improve precision?
  - flow-sensitive analysis
    - probably not [Ruf95]
  - subset-based FI
    - little [FFA00]
  - extended version of equality-based
    - little [DLFR01]
  - for equality-based FI
    - yes [FFA00]
- Assumptions
  - alloc site, pts-to, aggregates summarized, whole program
  - direct metric: [Ruf95, FFA00]
  - alias frequency; [DLFR01]

Context-Sensitivity

- Erik Ruf:
  - Fixed CS strategy may not be appropriate for client
    - Ex, traditional CS approach can yield bad code
  - Eagerly building clones inside a stand-alone ptr analysis is undesirable (potentially exponential)
  - Even highly parameterized standalone analyses pay costs for unneeded contexts
  - Ptr analysis should be integrated with client

Heap Modeling

- Shape analysis[SRW98, GH96,...] has high precision over alloc site naming
- Scalability of most precise analyses is in doubt
- Tom Reps:
  - plenty of interesting issues remain, such as
    - a better understanding of how to identify the important ingredients
    - efficiency
  - producing insights into other problems, such as system/memory configurations that can arise as a computation evolves

Aggregate Modeling

- Structs/objects
  - C/C++: absence of strong-typing makes struct field disambiguation nontrivial
    - many analyses didn't distinguish, exceptions [WL95, YHR99, ...]
  - Java's strong-type makes distinguishing fields easier
    - most Java analyses distinguish
  - Few empirical studies exist [YHR99,RLSZA01, LPH01,RMR01]

- Arrays
  - Only [RR99] distinguish array elements, no empirical studies
  - Leverage dependence analysis work?

Aggregate Modeling

- Rakesh Ghiya:
  Need to improve the basis ptr analysis info (especially malloc-site identification in the presence of user-defined memory management, and handling of fields), as opposed to solely focusing on incremental improvements in the propagation techniques.

Demand-Driven/Incremental

- Ptr analysis efficiency is important
- Precision requirements depends on the client
- Why not a demand-driven analysis?
  - Solutions exists for subset-based FI [R94,R98,D00,HT01,FRD00,RF01,DLFR01]
  - Open problem for FS
- How about an incremental analysis?
  - Some work [YRL99, VR01]

Java and OO Languages

- Most ptr analysis work is for C
- Does this work transfer to Java?
  - Good news: conservative fallback is not as bad (type info)
  - Good news: can't point to stack variables
  - Bad news: everything is a heap pointer
  - Promising approaches
    - Simpler shape analysis [GH96]
    - Type-based analyses [DMM97, FKS00]
- Need to revalidate studies based on C

Thoughts on Java

- Bjarne Steensgaard:
  - Many ptr analysis that worked well for C perform poorly for Java
  - Ptr analysis designers will adapt to programming languages/styles and output (tools and other analyses)
- Laurie Hendren:
  - Ex. finding properties of complex OO programs like verifying the correctness of iterators in Java

Incomplete Programs

- Most ptr analyses require whole program
- Michael Burke:
  - Component programming/library are becoming more prevalent
  - Whole program analysis less useful
  - Need parameterized ptr analyses wrt how they are configured in a full application
  - Some work [RRL99,RR01] exists, but problem not solved
- Manual Fahndrich:
  - Interface declarations that describe sharing and non-sharing relationships between data structures (shape descriptions) could lead to more precise ptr info

Engineering Insights

- Efficiency (time and memory) of a pointer analysis is important
- Careful engineering of a pointer analysis, particularly for FS, can dramatically improve its performance and scalability
- Conference ptr analysis papers
  - background
  - algorithm
  - empirical comparison
  - related work
  - implementation details
- Last section rarely gets written !!!
- To impact production systems, we must describe engineering

Terminology

- "context-sensitive" = "poly-variant"
- "context-insensitive" = "mono-variant"
- flow-insensitive analyses
  - equality = unification = Steensgaard-style = term or equality constraints
  - subset = Andersen-style = inclusion constraints
- pointer analysis, points-to analysis, alias analysis
- formulation
  - data flow, contraint-based, abstract interpretation, non-standard type inference

So, Have We Solved This Problem?

- No!
- Better question: will we ever "solve" this problem?
- Maybe, maybe not
  - need to focus on classes of clients
    - optimizations vs program understanding
  - new algorithms are nice, but we need strong empirical studies

- Maybe language designers will solve it for us?
  - latest ANSI C allows programmer to severely limit possible aliases
  - Fortran 90, Ada 95 require programmer to declare ptr targets

- But we still need more help for abstractions, such as collections

Thanks!

- Matthew Arnold
- Michael Burke
- Jong-Deok Choi
- Manuvir Das
- Amer Diwan
- Manuel Fahndrich
- Stephen Fink
- David Grove
- Rakesh Ghiya
- Laurie Hendren
- Susan Horwitz
- Bill Landi
- G. Ramalingam
- Tom Reps
- Erik Ruf
- Barbara Ryder
- Mooly Sagiv
- Bjarne Steensgaard