Practical fine-grained static slicing of optimized code

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(work done at Microsoft Research)

Simple example

```
a = foo();
b = bar();
c = a * b;
d = a - b;
e = b + c;
f = c * e;
g = e - c;
h = f / g;
i = g * h;
j = g / 2;
... j ...
```

```
a = foo();
b = bar();
c = a * b;
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e = b + c;
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i = g * h;
j = g / 2;
... j ...
```

Example: function calls and pointers

```
main(int a, int b)
{
  int sum = swapsum(&a, &b);
  printf("%d %d %d", a, b, sum);
}

swapsum(int *x, int *y)
{
  int z;
  z = *x;
  *x = *y;
  *y = z;
  z = (*x) + (*y);
  return(z);
}
```

```
main(int a, int b)
{
  int sum = swapsum(&a, &b);
  printf("%d %d %d", a, b, sum);
}

swapsum(int *x, int *y)
{
  int z;
  z = *x;
  *x = *y;
  *y = z;
  z = (*x) + (*y);
  return(z);
}
```

Applications of slicing

Closure slicing: visualize dependences

- **program understanding**
- **maintenance**
- **test coverage**
- **debugging**

Executable slicing: produce binary

- **specialization**
- **parallelization**
- **testing**
- **integration of program versions**

Dynamic slicing: execution tracing

Outline

- Motivation
- Basic slicing algorithm
- Interprocedural
- Pointers and aggregate values
- Optimized code
- Executable slicing
- Conclusion

Simple slicing algorithm

For graph-based program representation:

Just graph reachability!

The value dependence graph (VDG)

Sparse, functional, parallel representation for imperative programs

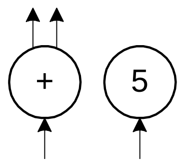
Insights:

- **Only values matter**
- **Original names and control flow are incidental**

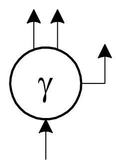
Consequences:

- **All values are explicit**
- **Select values, not control paths**
- **Control flow represented by function calls**

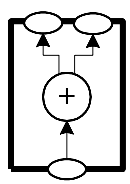
Components of the value dependence graph



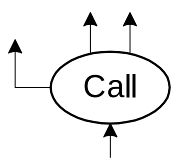
operation nodes



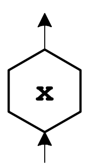
selectors

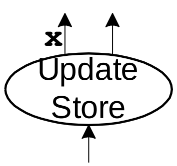


closures (functions)



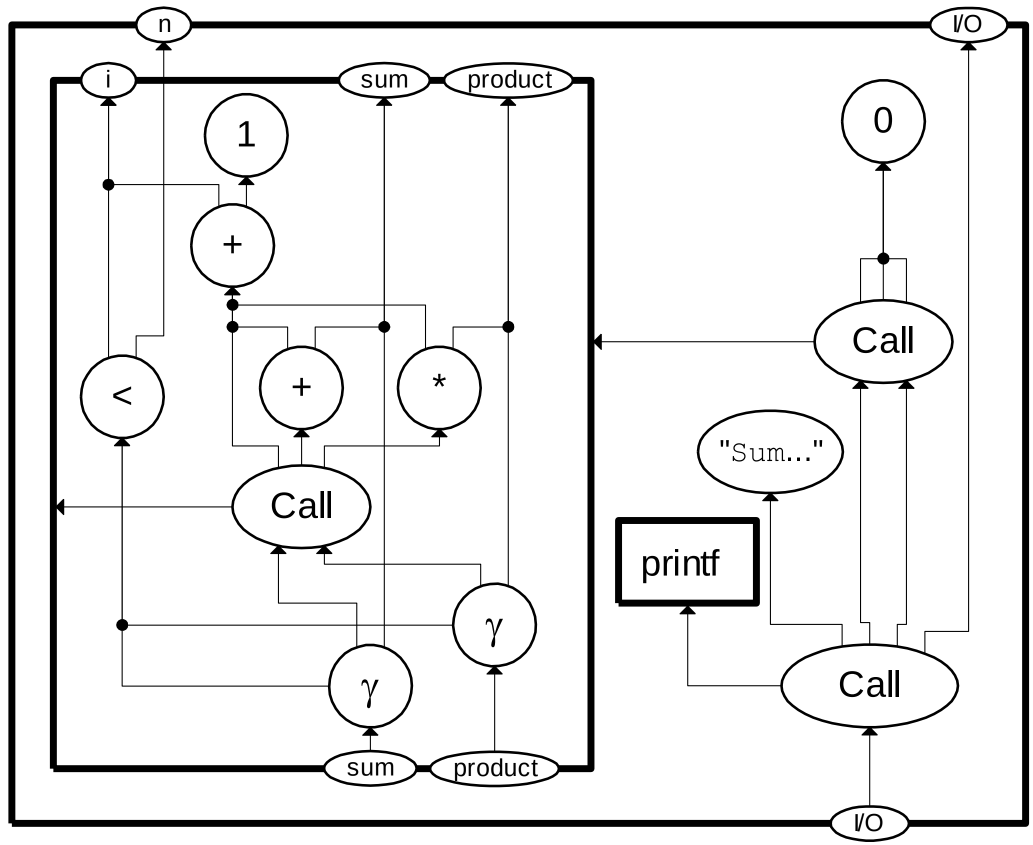
function calls





memory lookups (load instructions)
memory assignments (store instructions)

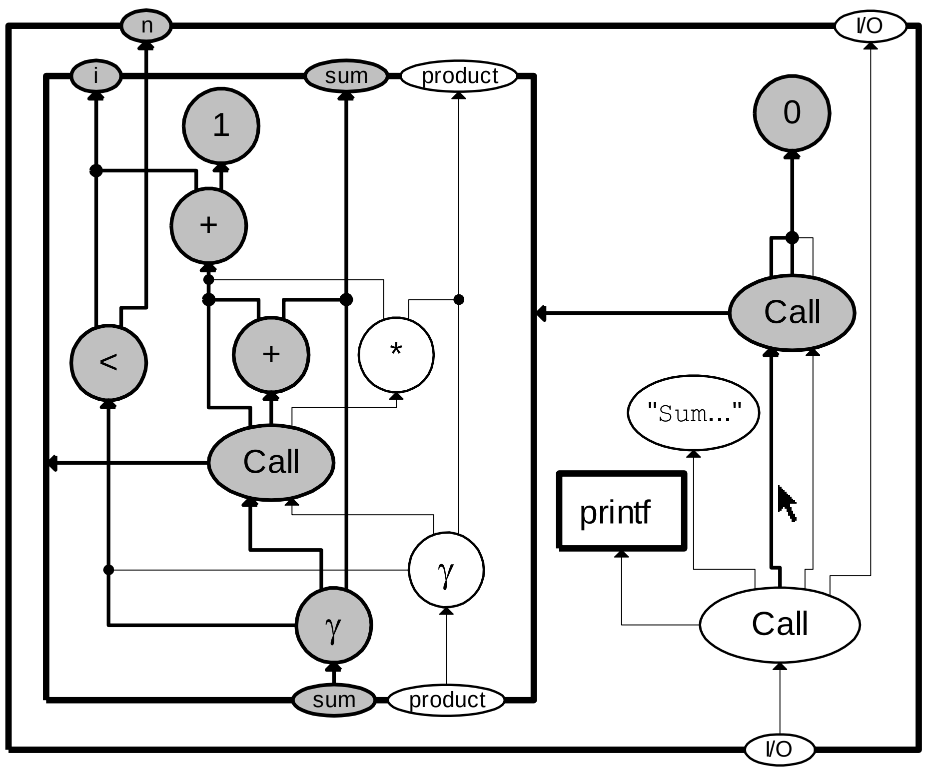
Example VDG




```
void sum_product(int n)
{
  int sum = 0;
  int product = 0;
  int i = 0;

  while (i++ < n)
    { sum = sum + i;
      product = product * i;
    }
  printf("Sum %d, product %d",
         sum, product);
}
```

Example VDG, sliced

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   int i = 0;

   while (i++ < n)
     { sum = sum + i;
       product = product * i;
     }
   printf("Sum %d, product %d",
          sum, product);
}
```

The VDG is good for slicing

- **Simple, fast algorithm**
- **Fine granularity**
- **One graph directly links producers and consumers**
- **All values are explicit**

Slicing criteria

Expression results, not whole computations

Any expression

Any result, including unnameable ones

Unreferenced variables

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Interprocedural

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Interprocedural slicing

Goals:

- sensitive to calling context
- do not include entire procedure or all calls
- efficient
- omit irrelevant procedures

Obvious solution: graph reachability

- call results ➲ procedure returns
- formal parameters ➲ actual parameters

This does not satisfy our goals.

Interprocedural slicing (solution)

- **Summarize dependences of returns on formals**
- **Separately include appropriate portions of body**
- **When slicing criterion is within a procedure, include all calls**

```
int increment(int i);
{ return (i+1); }

a = foo();
b = bar();
x = increment(a);
y = increment(b);
```

```
int increment(int i);
{ return (i+1); }

a = foo();
b = bar();
x = increment(a);
y = increment(b);
```

This meets our goals.

Procedure summary dependences

Optimistic forward dataflow problem

- operation result depends on what the operands depend on
- for calls, use current approximation as transfer function
- reprocess calls when new approximation becomes available
- iterate until fixpoint is reached

Complexity

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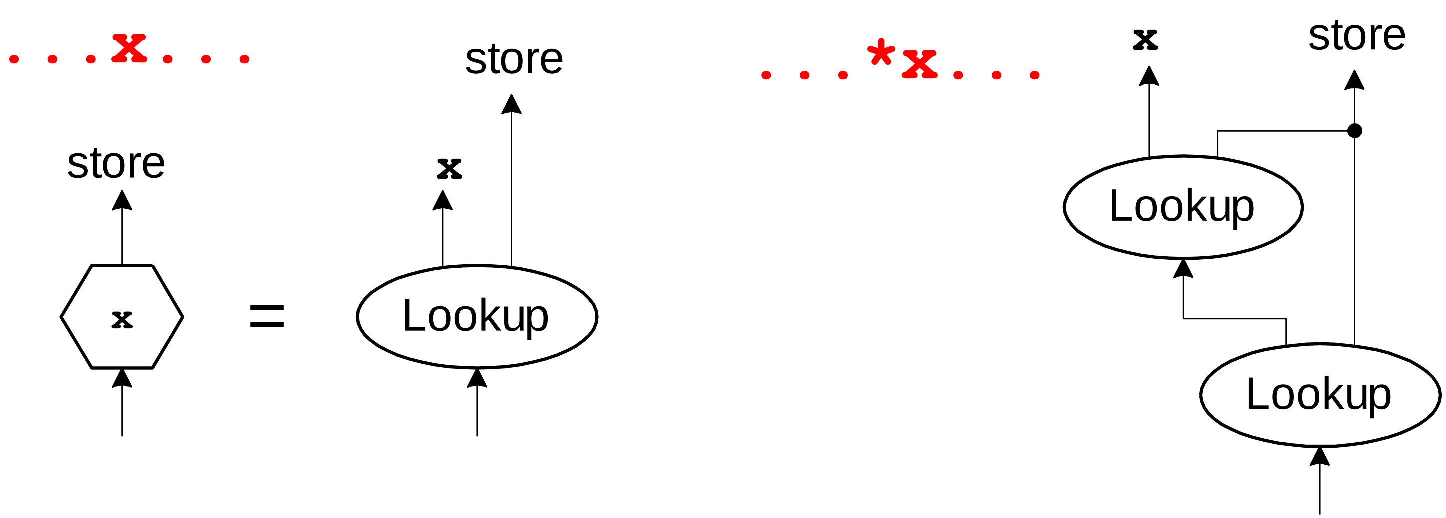
Pointers

Support arbitrary pointer manipulations

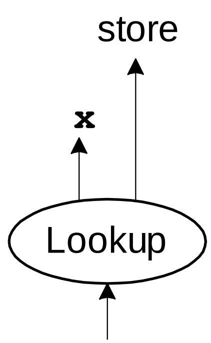
Points-to analysis gives possibly referenced locations

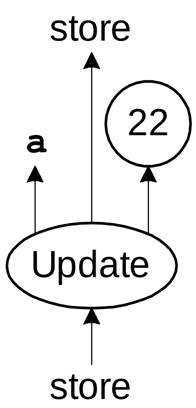
For lookup, slice on location and (part of) store



Treat store as a collection

Slice on every possibly referenced location.





Slice continues at

- **killing def: location, value** **(use pointer equality)**
- **preserving def: location, value, store**
- **other: store**

Aggregate values

Just like the store.

Complexity

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Slicing optimized code

Improve:

- **dependences**
- **liveness**
- **computations**
- **overhead**

The hardware runs optimized code

Slice reflects intermediate representation's semantics

Correspondence with source code

Need many-to-many mappings

- VDG node ➲ source text
- source text ➲ VDG node

Maintain a separate source graph

- initially isomorphic to VDG
- transformations modify VDG and source correspondences
- slicing traverses both graphs in tandem
- slice display defaultly highlights only appropriate sources

History mechanism

Source graphs are never side-effected or removed

Transformations add to source graph

Mappings no longer necessarily inverses

This enables

- **undoing transformations**
- **explaining changes**
- **slice according to naive interpretation**
- **slice dead code**
- **statement-oriented display**

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Executable slicing

Goal: executable binary

Applications:

- **specialization**
- **parallelization**
- **testing**
- **integration of program versions**

Compilable slicing

Traditional technique for executable slicing:

- **subset the original program**
- **compile using a standard compiler**

Compilable slicing tradeoffs

Retains context, comments, formatting, names

Include undemanded portions of the program to satisfy syntactic constraints

- **multi-valued computation**
- **function call parameters**
- **variable assignments**
- **control flow: `goto`, `continue`, `break`**

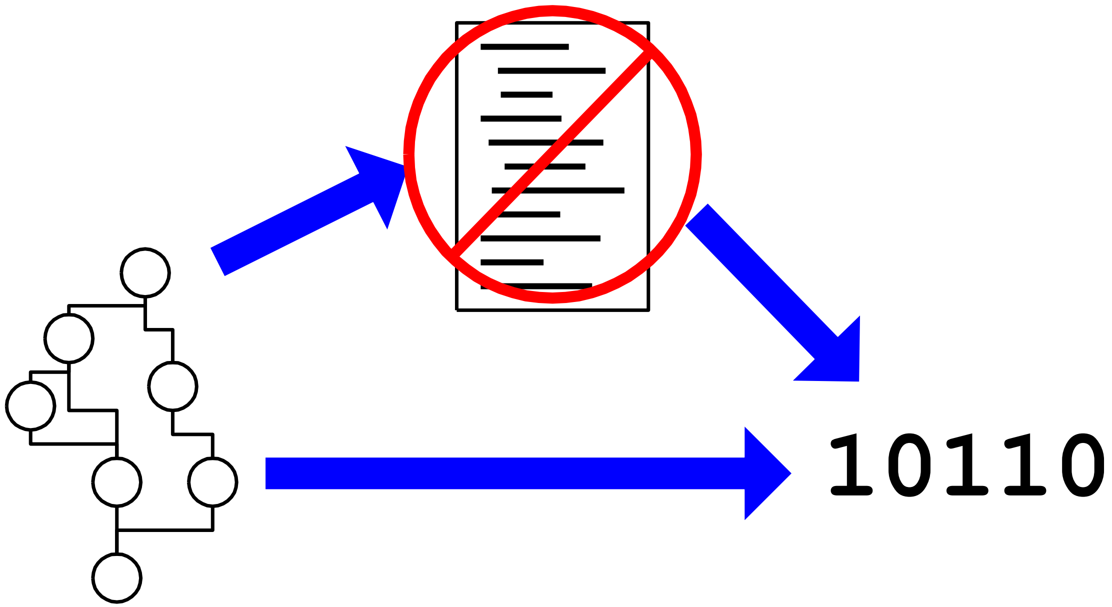
Limits optimization

Hard to undo

Our executable slicing solution

Generate code directly from slice

For debugging, use original program



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Status

Part of a programming environment

Handles C (except `longjmp`)

Written in Scheme

Integrated with Emacs

Future work

Quasi-static slicing

Dynamic slicing

History mechanism

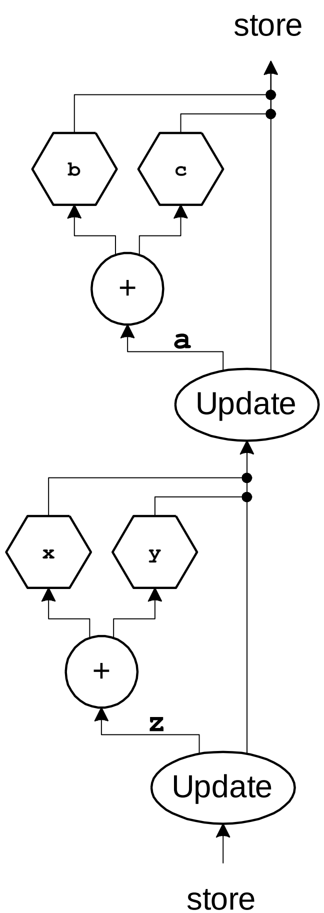
User interface alternatives

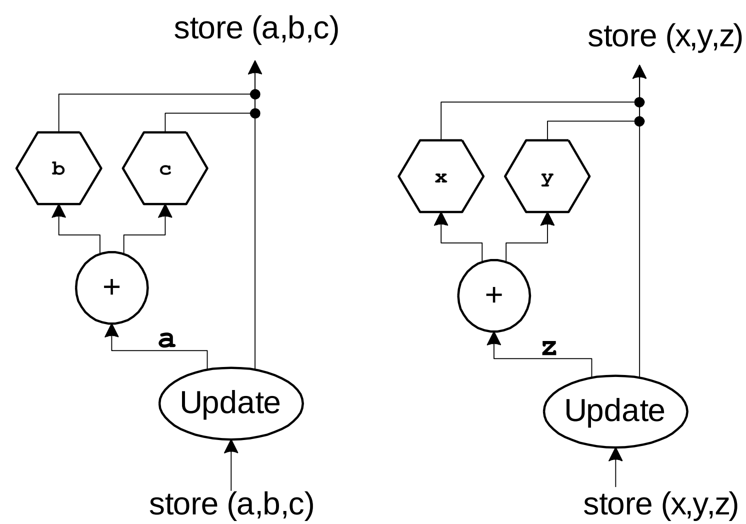
Tests on real users

Debugging optimized code

Ambiguity in program points

```
z = ...;
a = b + c;
z = x * y;
```





Comparing the VDG and PDG

Which PDG?

VDG:

- **no implicit quantities**
- **better integration with programming environment**
- **easier analysis, transformation**
- **cleaner interprocedural representation**
- **single graph**
- **finer granularity**