C⚙de analysis *and* transf⚙rmation

Inter-procedural CAT

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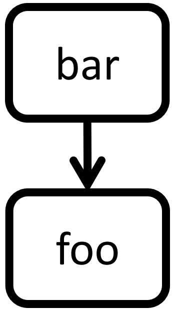
Procedures/functions

- Abstraction
  - Cornerstone of programming
  - Introduces barriers to analysis



Is x constant?

```
void bar (void){
  x = 5;
  px = &x;
  foo(px);
  y = x + 5;
}
```

- So far looked at **intra-procedural** analysis
  - Analyzing a single procedure

- **Inter-procedural** analysis uses calling relationships among procedures (Call Graph)
  - Enables more precise analysis information

Inter-procedural analysis

Goal: Avoid making overly conservative assumptions about the effects of procedures and the state at call sites

Terminology

```
int a, e;                    // Globals
void foo(int *b, int *c){    // Formal parameters
  (*b) = e;
}
bar(){
  int d;                     // Local variables
  foo(a, d);                 // Actual parameters
}
```

Inter-procedural analysis vs. inter-procedural transformation

Inter-procedural analysis

- Gather information across multiple procedures (up to the entire program)
- Can use this information to improve intra-procedural analyses and transformation (e.g., CP)

Inter-procedural transformation

- Code transformations that involve multiple procedures e.g., Inlining, procedure cloning, function specialization

Outline

① Sensitivity of analysis

② Single compilation

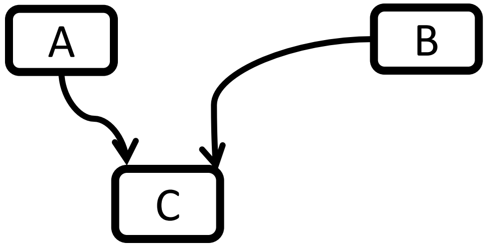
③ Separate compilations

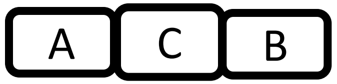
④ Caller -> callee vs. callee -> caller propagations

⑤ Final remarks

Sensitivity of intra-procedural analysis

- Flow-sensitive vs. flow-insensitive





Flow sensitivity example

Is x constant?

```
void f (int x){
  A: x = 4;
  ...
  B: x = 5;
}
```

Flow-sensitive analysis

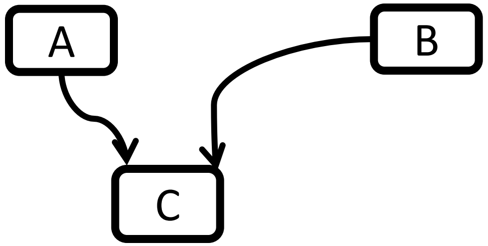
- It can compute one answer for every program point
  - x is 4 after A
  - x is 5 after B
- Requires iterative data-flow analysis or similar technique

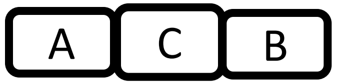
Flow-insensitive analysis

- It computes one answer for the entire procedure
  - x is not constant
- Can compute in linear time
- Less accurate (ignores control flows)

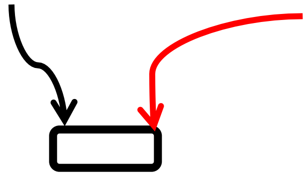
Sensitivity of intra-procedural analysis

- Flow-sensitive vs. flow-insensitive



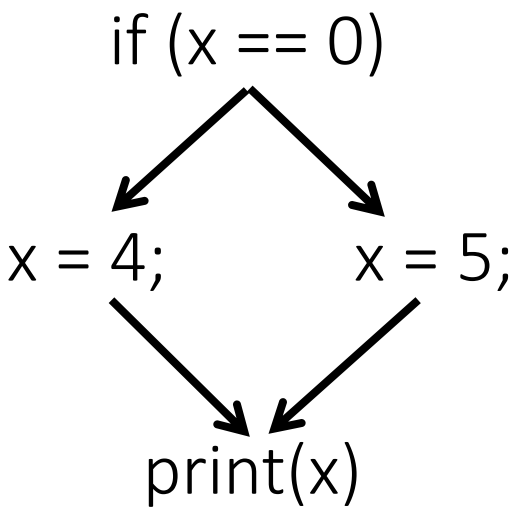


- Path-sensitive vs. path-insensitive



Path sensitivity example

Is x constant?



Path-sensitive analysis

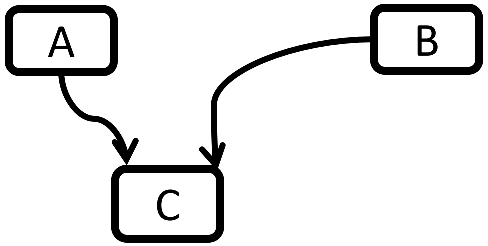
- Computes one answer for every execution path
  - x is 4 at print(x) if you came from the left path
  - x is 5 at print(x) if you came from the right path
- Subsumes flow-sensitivity
- Very expensive

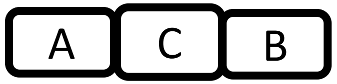
Path-insensitive analysis

- Computes one answer for all path
  - x is not constant at print(x)

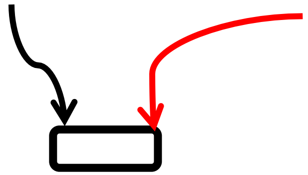
Sensitivity of inter-procedural analysis

- Flow-sensitive vs. flow-insensitive





- Path-sensitive vs. path-insensitive



- Context-sensitive vs. context-insensitive

Context sensitivity example

Is x constant?

```
a = id(4);        b = id(5);

id (x) { return x;}
```

Context-sensitive analysis

- It can compute one answer for every call-site
    - x is 4 in the first call
    - x is 5 in the second call
- Re-analyzes callee for each caller

Context-insensitive analysis

- It computes one answer for all call-sites:
    - x is not constant
- Perform one analysis independent of callers
- Suffers from unrealizable paths:
    - Can mistakenly conclude that id(4) can return 5 because
      we merge information from all call-sites

Call graph

- First problem: how do we know what procedures are called from where?
  - Especially difficult in higher-order languages, languages where functions are values
  - What about C programs?
  - We'll ignore this for now

```
void foo (int a, int (*p_to_f)(int v)){
  int l = (*p_to_f)(5);
  a = l + 1;
  return a;
}
```

- Let's assume we have a (static) **call graph**
  - Indicates which procedures can call which other procedures, and from which program points

Call graph example

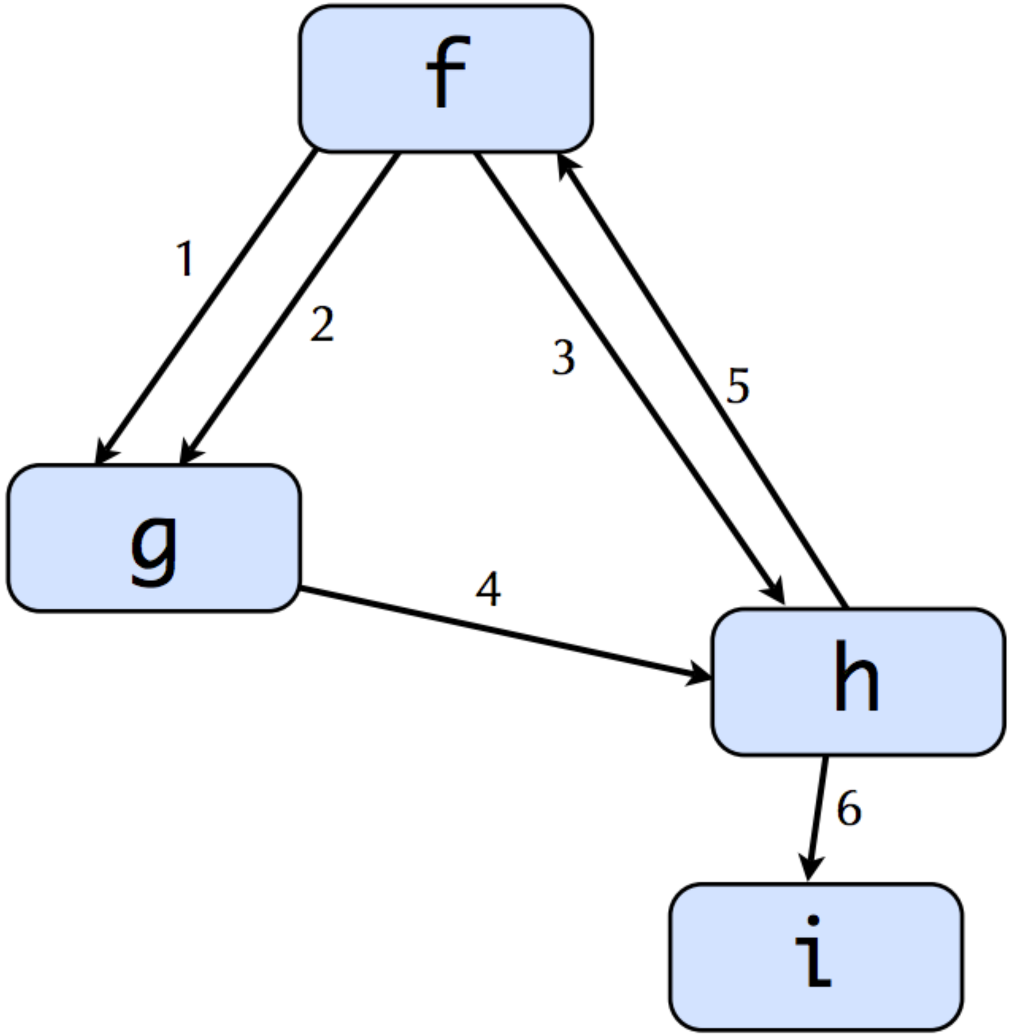
```
f() {
   1:  g();
   2:  g();
   3:  h();
}

g() {
   4: h();
}

h() {
   5: f();
   6: i();
}

i() { … }
```

From now on we assume we have a static call graph



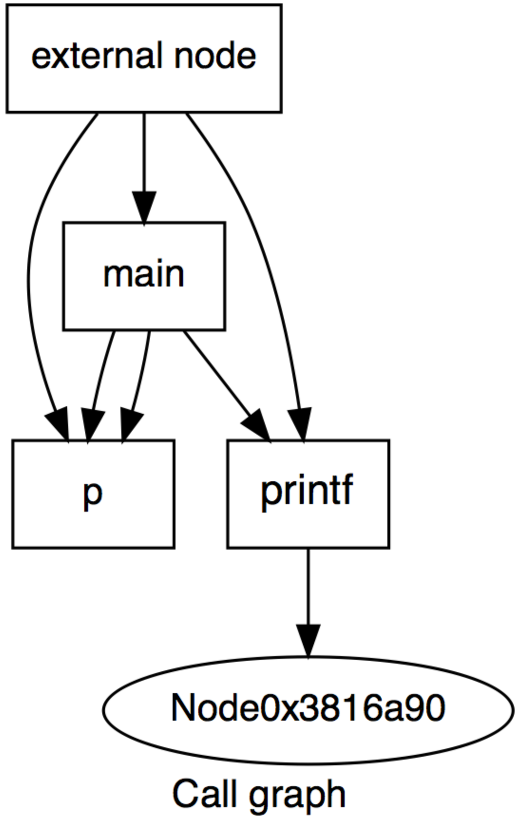
Generating a call graph with LLVM

- From the command line:

opt -dot-callgraph program.bc -disable-output

(see test0)

- From your pass:
  - Explicit iteration
    - LLVM_callgraph/llvm/[0-4]



DEMO

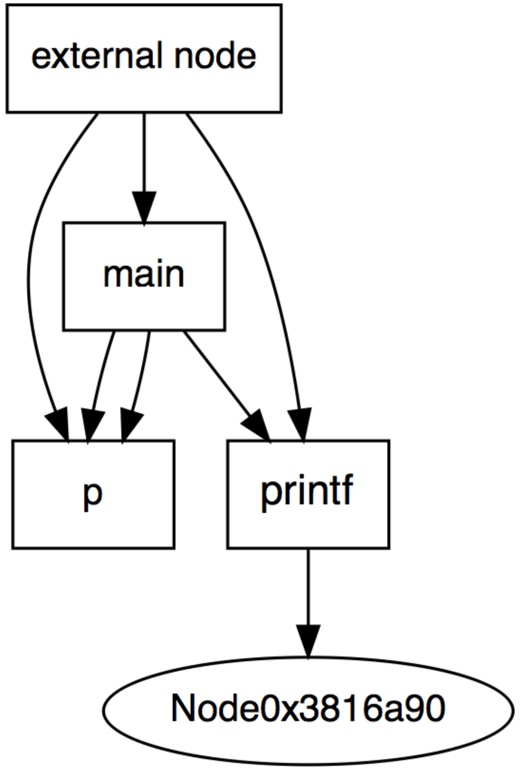
Generating a call graph with LLVM

- From the command line:

opt -dot-callgraph program.bc -disable-output

(see test0)

- From your pass:
  - Explicit iteration
    - LLVM_callgraph/llvm/[0-4]
  - CallGraphWrappingPass
    - LLVM_callgraph/llvm/[5-6]



Call graph

Using CallGraphWrappingPass

- Declaring your pass dependence

```
void getAnalysisUsage(AnalysisUsage &AU) const override {
  AU.addRequired< CallGraphWrapperPass >();
```

- Fetching the call graph

```
bool runOnModule(Module &M) override {
  errs() << "Module \"" << M.getName() << "\"\n";
  CallGraph &CG = getAnalysis<CallGraphWrapperPass>().getCallGraph();
```

Using CallGraphWrappingPass

- From a Function to a node of the call graph

```
errs() << " Function \"" << F.getName() << "\"\n";
CallGraphNode *n = CG[&F];
```

- From node to callees

```
for (auto callee : *n){
  auto calleeNode = callee.second;
  auto callInst = callee.first;
```

- From node to Function

```
auto calleeF = calleeNode->getFunction();
errs() << "   \"" << calleeF->getName() << "\"";
```

DEMO

Outline

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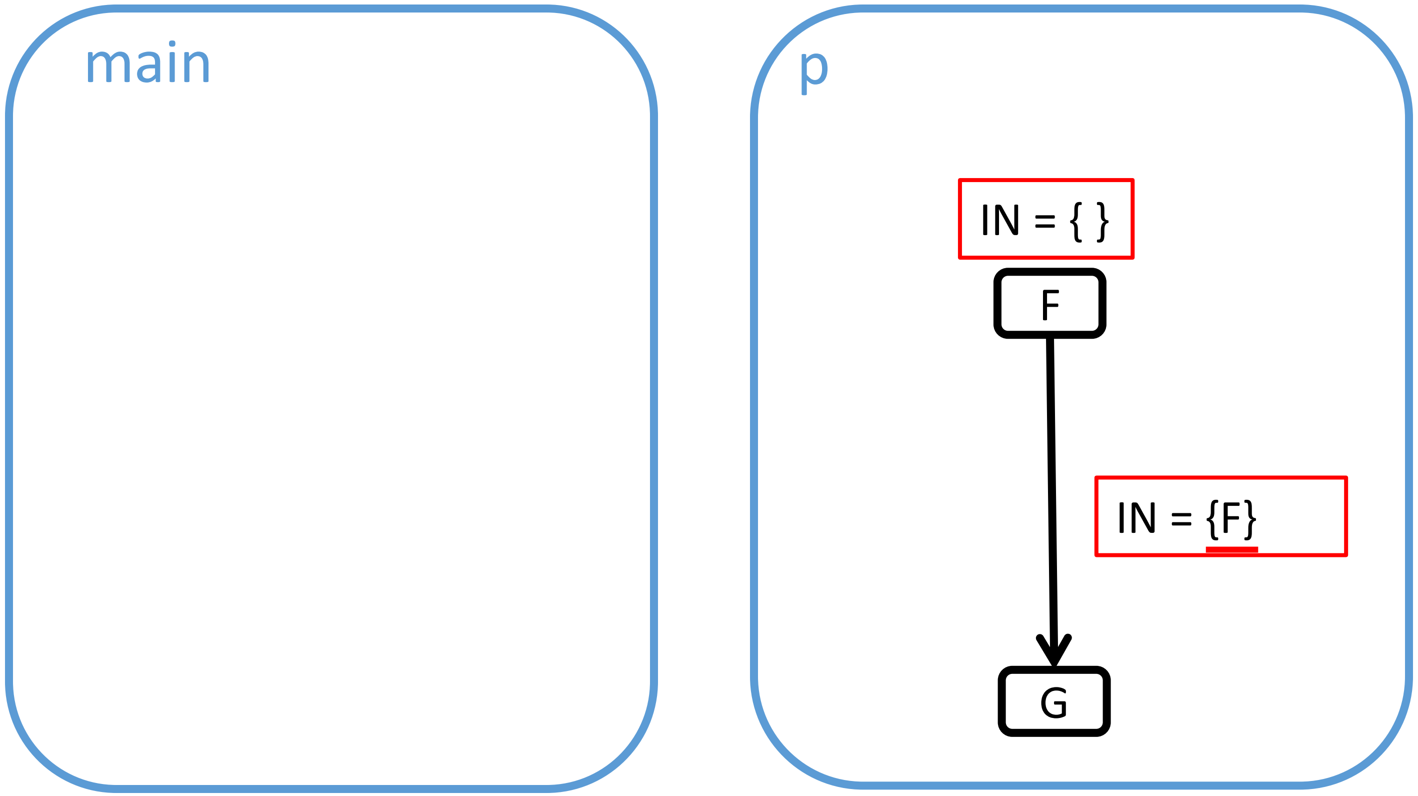
Intra-procedural dataflow analysis

- How have we been performing reaching definitions so far?

main() {
 A: x = 7;
 B: r = p();
 C: y = 80;
 D: t = p();
 E: print t, r;
}
int p (void) {
  F: m = 1;
  G: return ~~m~~ 1;
}



Intra-procedural dataflow analysis

- How have we been performing reaching definitions so far?

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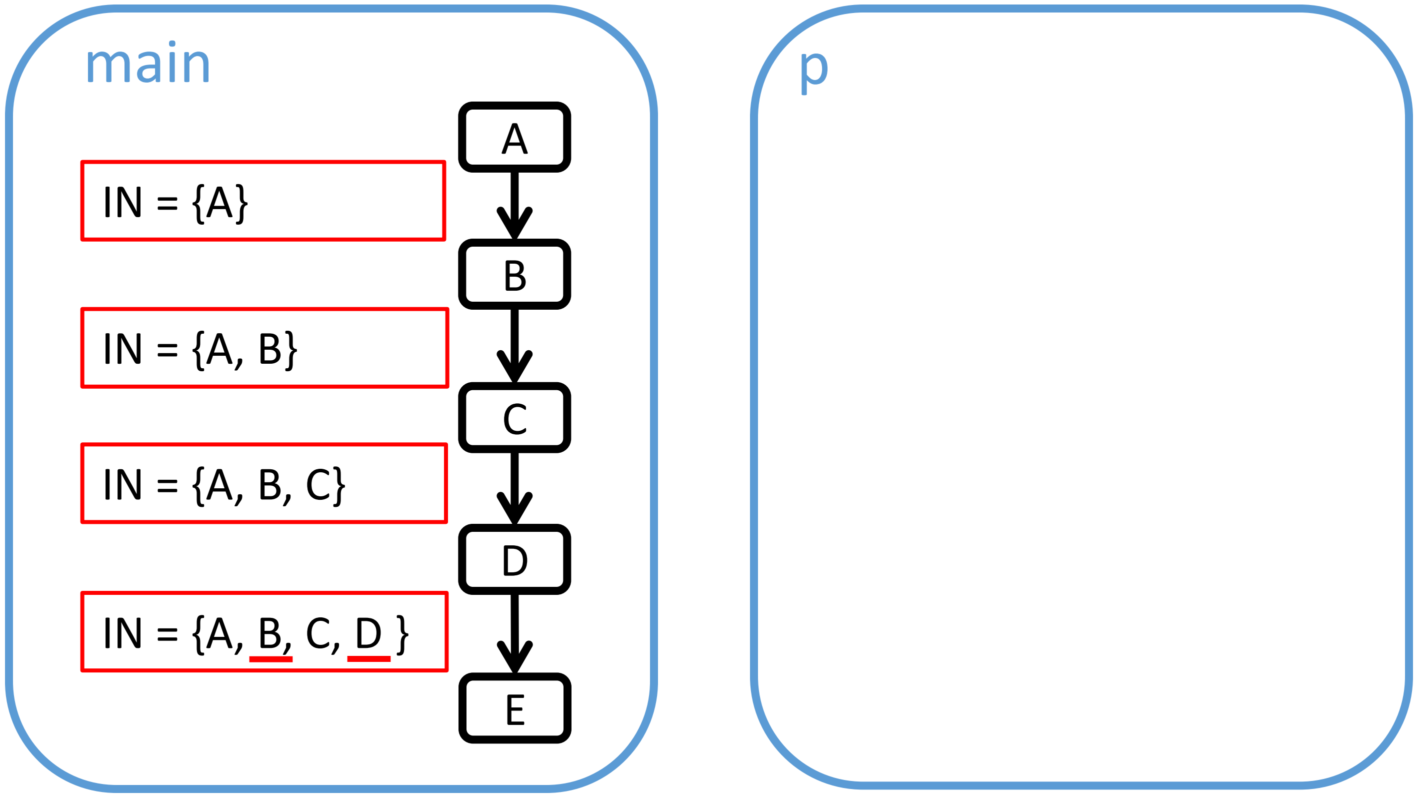
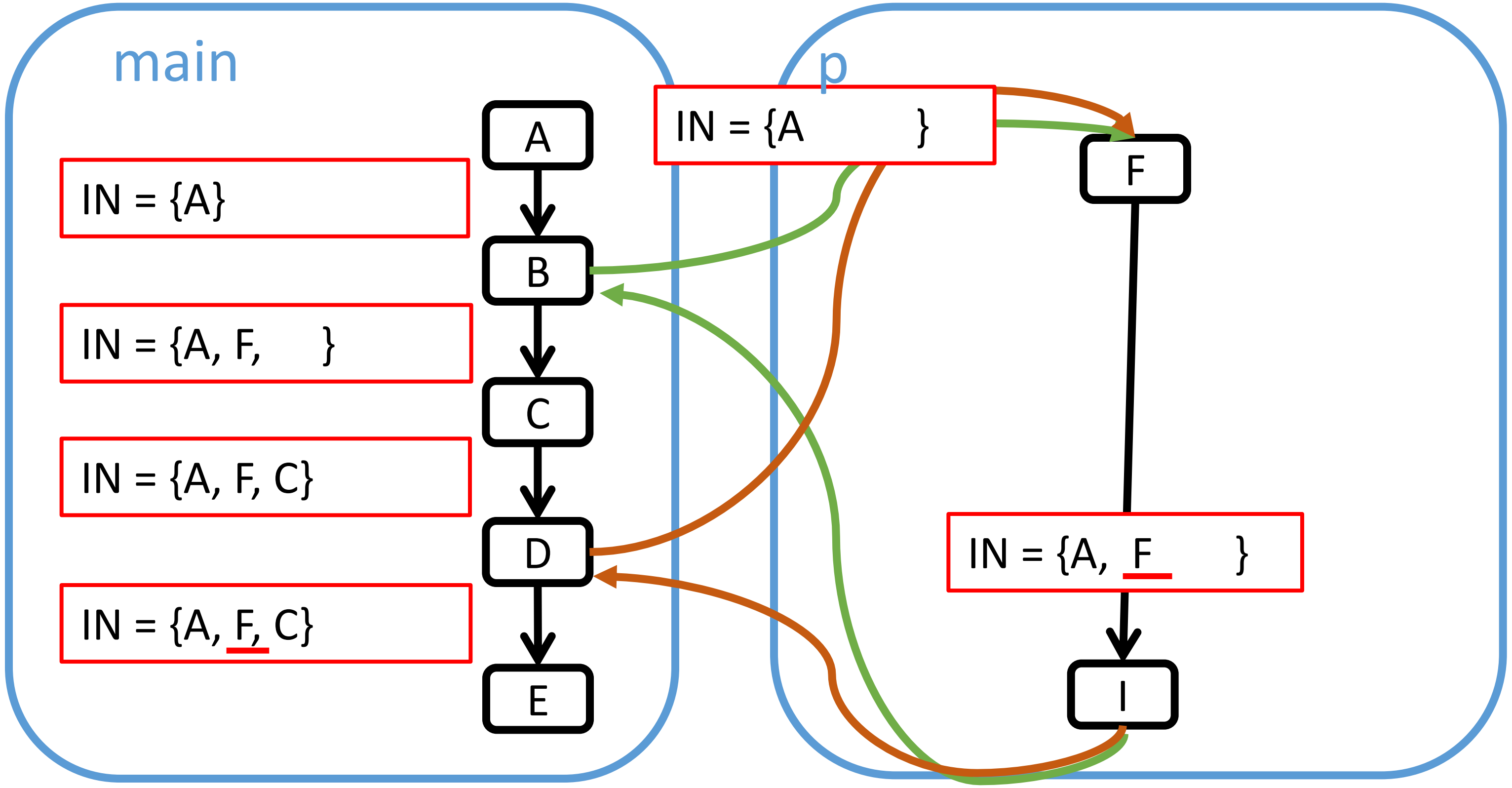


Inter-procedural dataflow analysis flow-sensitive

- How can we handle procedure calls?
- Obvious idea: make one big CFG (**control-flow supergraph**)

- Better accuracy
- Worst analysis time
  - No separate analysis

main() {
 A: x = 7;
 B: r = p();
 C: y = 80;
 D: t = p();
 E: print ~~t~~ 1, ~~r~~ 1;
}
int p (void) {
 F: m = 1;
 G: return ~~m~~ 1;
}

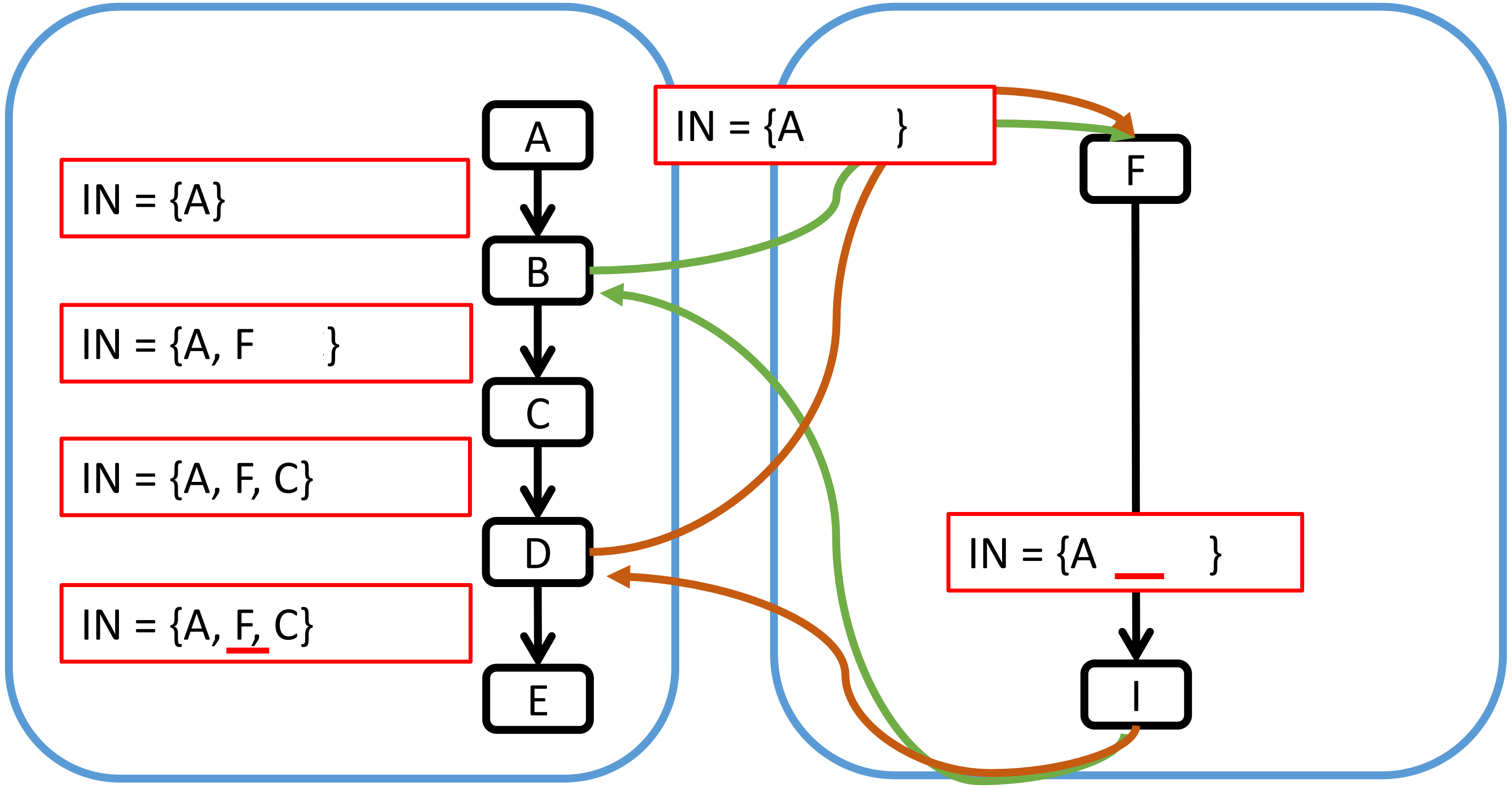


Inter-procedural dataflow analysis flow-sensitive

- Better accuracy
- but not enough

- Make one big CFG (**control-flow supergraph**)

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: m = v + 1
  G: return m;
}
```



Inter-procedural dataflow analysis flow-sensitive

- Better accuracy
- but not enough

- Make one big CFG (**control-flow supergraph**)

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: m = v + 1
  G: return m;
}
```

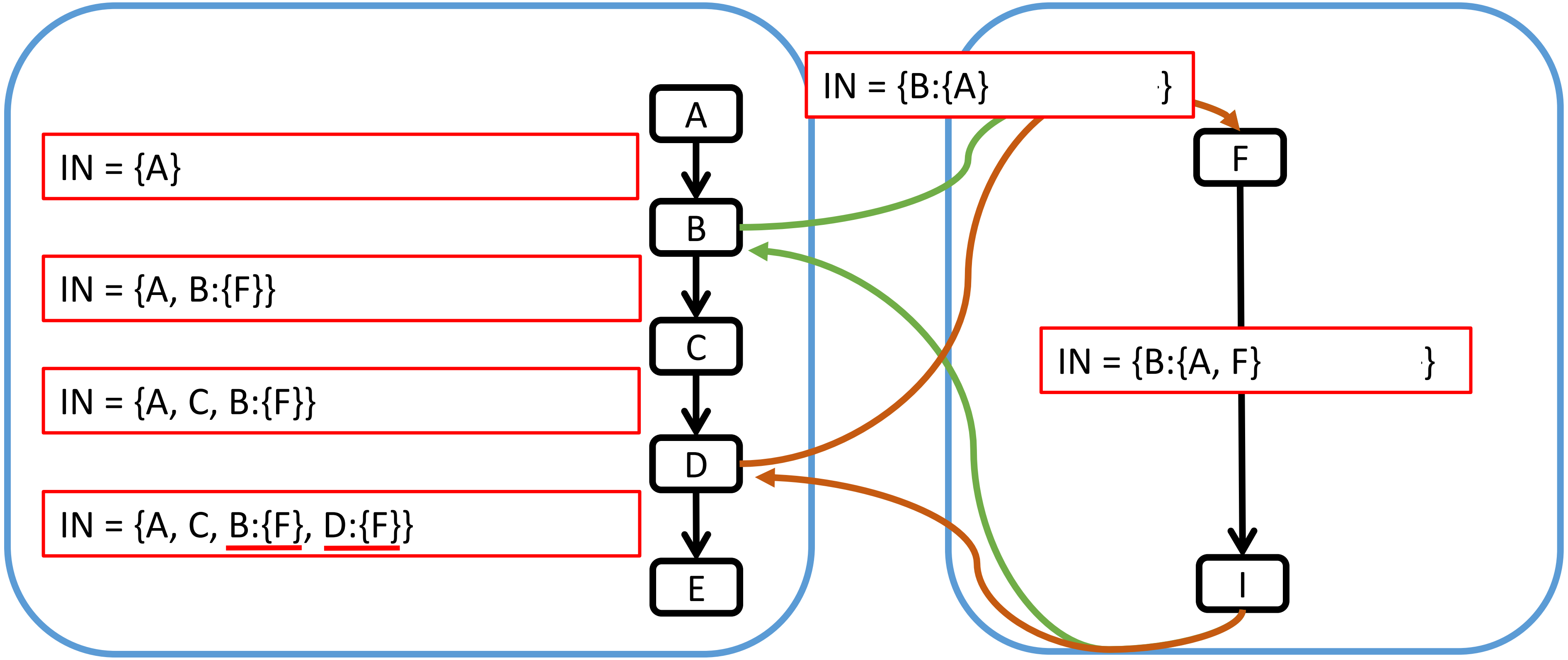
- Problem: v is seen from the point of view of all call sites
- How to address this problem?

Inter-procedural dataflow analysis flow/context-sensitive

- Make one big CFG (**control-flow supergraph**)

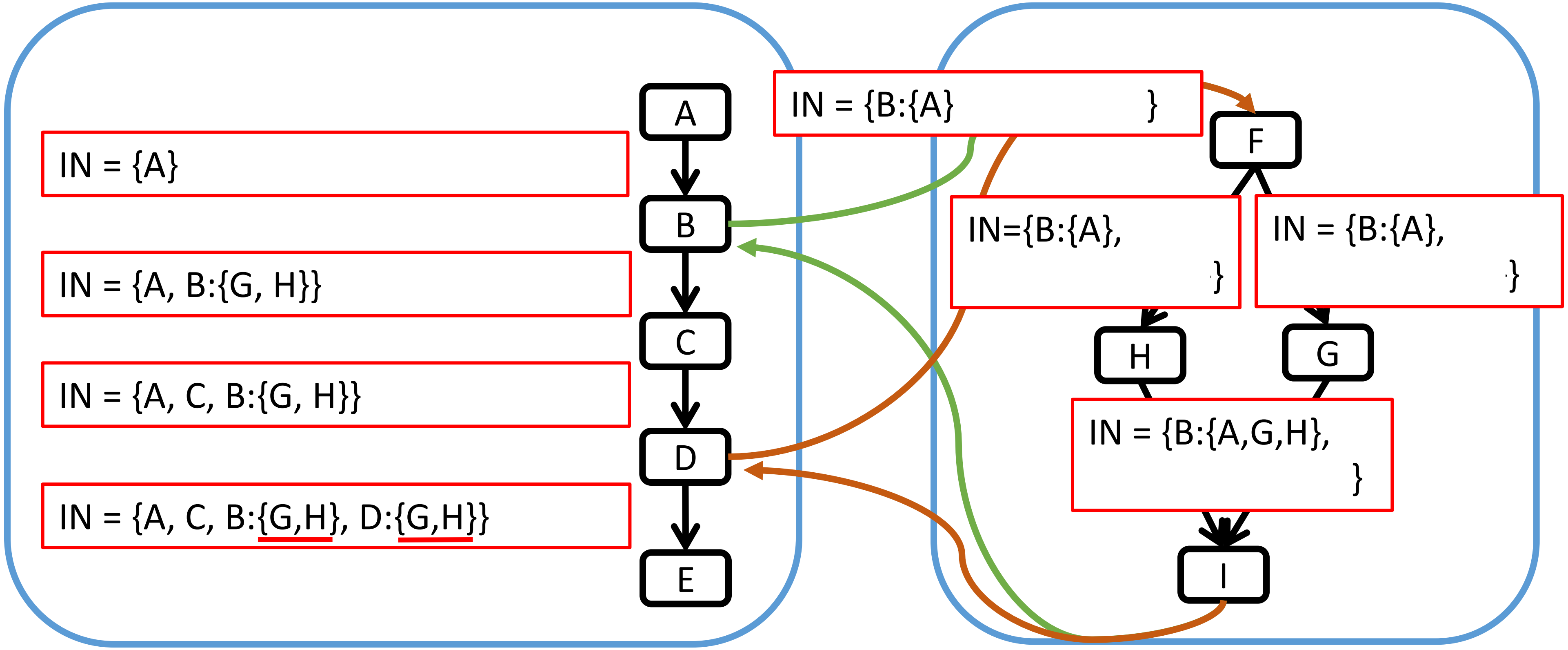
main() {
A: x = 7;
B: r = p(x);
C: y = 80;
D: t = p(y);
81, 8
E: print ~~t~~, ~~r~~;
}
int p (int v) {
F: m = v + 1
G: return m;
}

- Better accuracy
- More memory/analysis time



Inter-procedural dataflow analysis flow/context-sensitive

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
      else
  H:      m = 2;
   I: return m;
}
```



- Even an inter-procedural flow- and context- sensitive analysis isn’t able to perform the constant propagation we want
- We need to make our analysis even more complex

- Since this seems hard, let’s try something easier
- Let’s try to follow a simpler solution:
    - We copy the body of the callee inside the caller
    - Function inlining

Inter-procedural code transformation: function inlining

- Function inlining:
  - Use a new copy of a procedure's CFG at a call site
  - Adjust copied code within the caller
    (e.g., rename variables, map formal parameters to actual parameters)

```
void myF (void){
    int r0 = myG(3, 4);



    int r1 = r0 + 1;
    return r1;
}
```

Let's inline this call

```
int myG (int p0, int p1){
    int v0 = p0 + p1;
    return v0;
}
```

Inter-procedural code transformation: function inlining

- Function inlining:
  - Use a new copy of a procedure’s CFG at a call site
  - Adjust copied code within the caller
    (e.g., rename variables, map formal parameters to actual parameters)

```
void myF (void){
    int p0 = 3; int p1 = 4;
    int v0 = p0 + p1;
    int r0 = v0;
    int r1 = r0 + 1;
    return r1;
}
```

int r0 = myG(3, 4);

```
int myG (int p0, int p1){
    int v0 = p0 + p1;
    return v0;
}
```

Inter-procedural code transformation: function inlining

- Function inlining:
  - Use a new copy of a procedure’s CFG at a call site
  - Adjust copied code within the caller
    (e.g., rename variables, map formal parameters to actual parameters)
- In LLVM:
  - You don’t need to implement this transformation, it already exists ☺
  - InlineResult InlineFunction(CallBase *, InlineFunctionInfo &, …)

Extra parameters are optional

```
InlineFunctionInfo  IFI;
if (InlineFunction(call, IFI).isSuccess()) {
   …
} else { … }
```

#include "llvm/Transforms/Utils/Cloning.h"

Function inlining in LLVM and alias analysis

- InlineResult InlineFunction(
  CallBase &, InlineFunctionInfo &,
  AAResults *CalleeAAR = nullptr,
  bool InsertLifetime = true , ...)

```
void f (){
    ...  // pre_g
    call g()
    ...  // post_g
}
void g(){
   %1 = alloca(...)
   ... // g_body
}
```

Function inlining

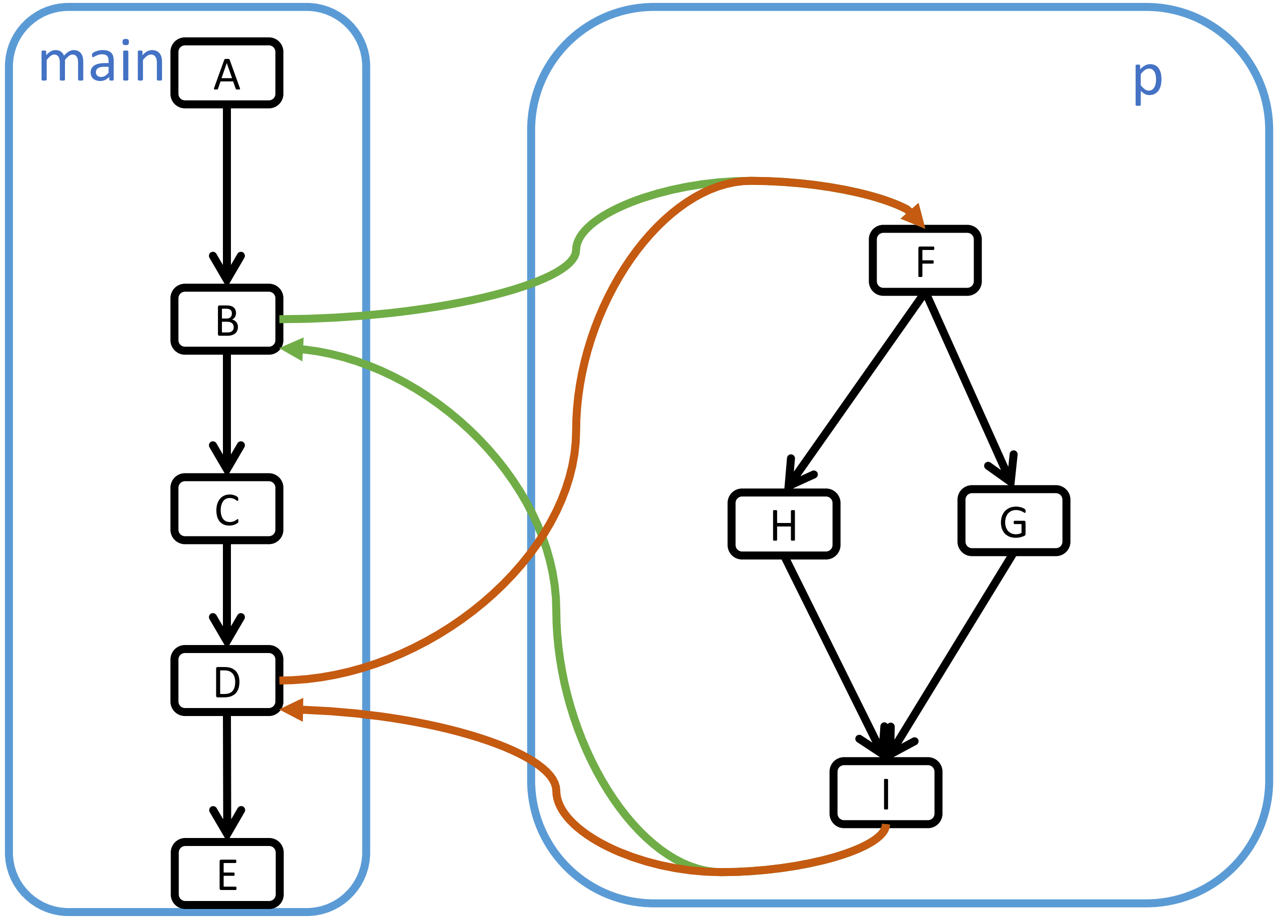
```
void f (){
    %1 = alloca()
    ... // pre_g
    ... // g_body
    ... // post_g
}
```

New
live range of %1

But we know %1 can only be used (directly or indirectly) within g_body

Inter-procedural code transformation: function inlining

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:       m = 1;
       else
  H:       m = 2;
   I: return m;
}
```



Example of function inlining: inline the callee of B

Inter-procedural code transformation: function inlining

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:       m = 1;
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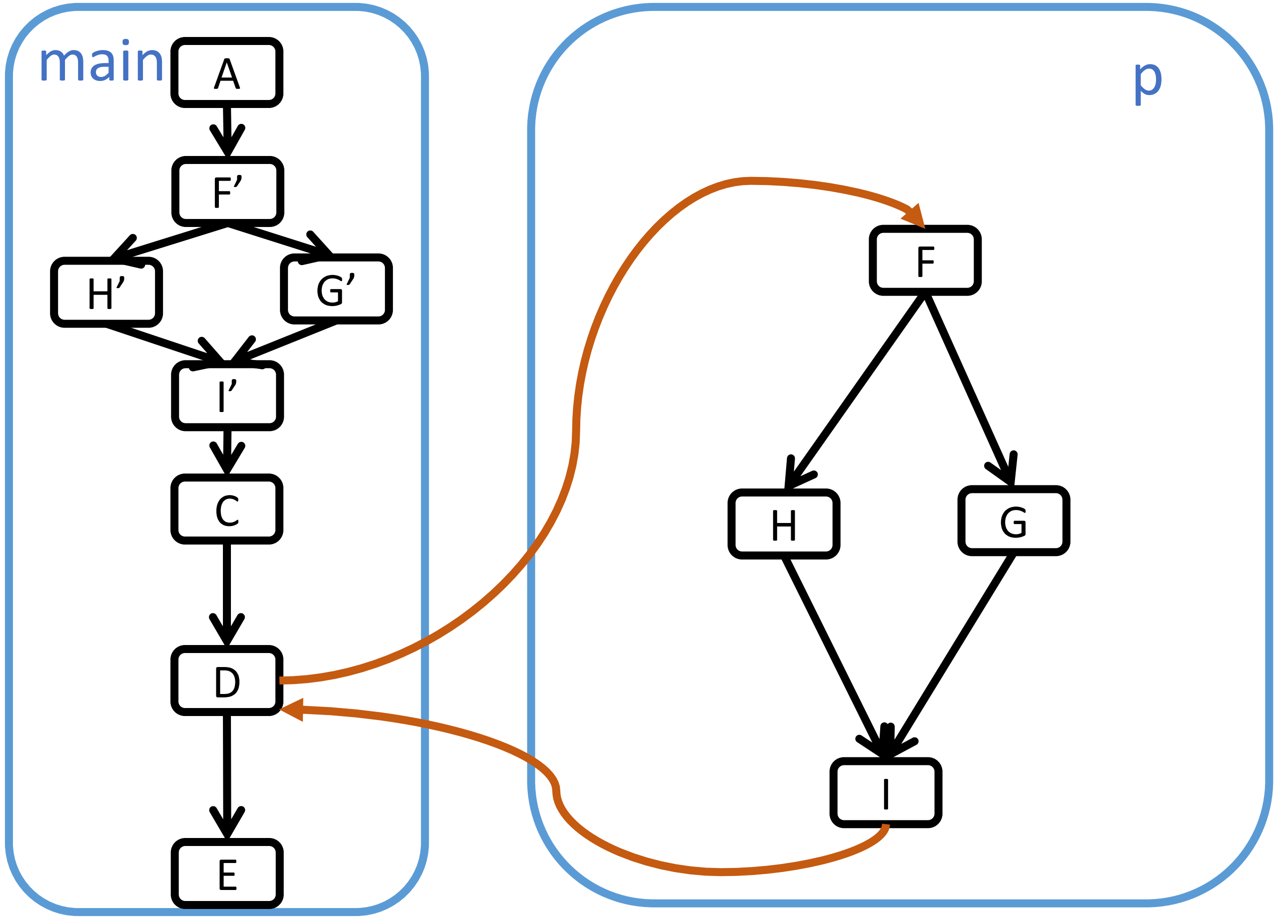
   I: return m;
}
```



Another example of function inlining: inline the callee of D

Inter-procedural code transformation: function inlining

```
main() {
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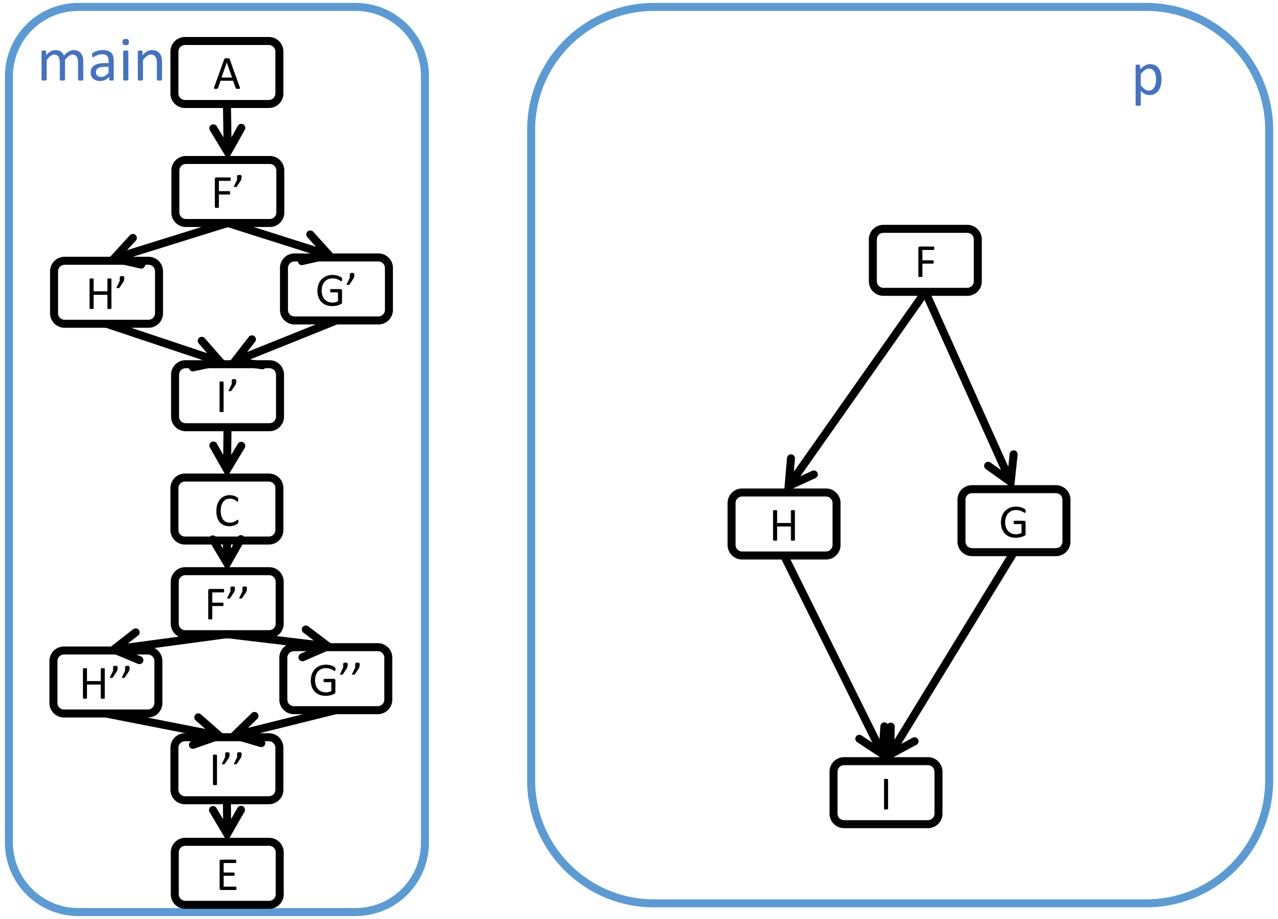
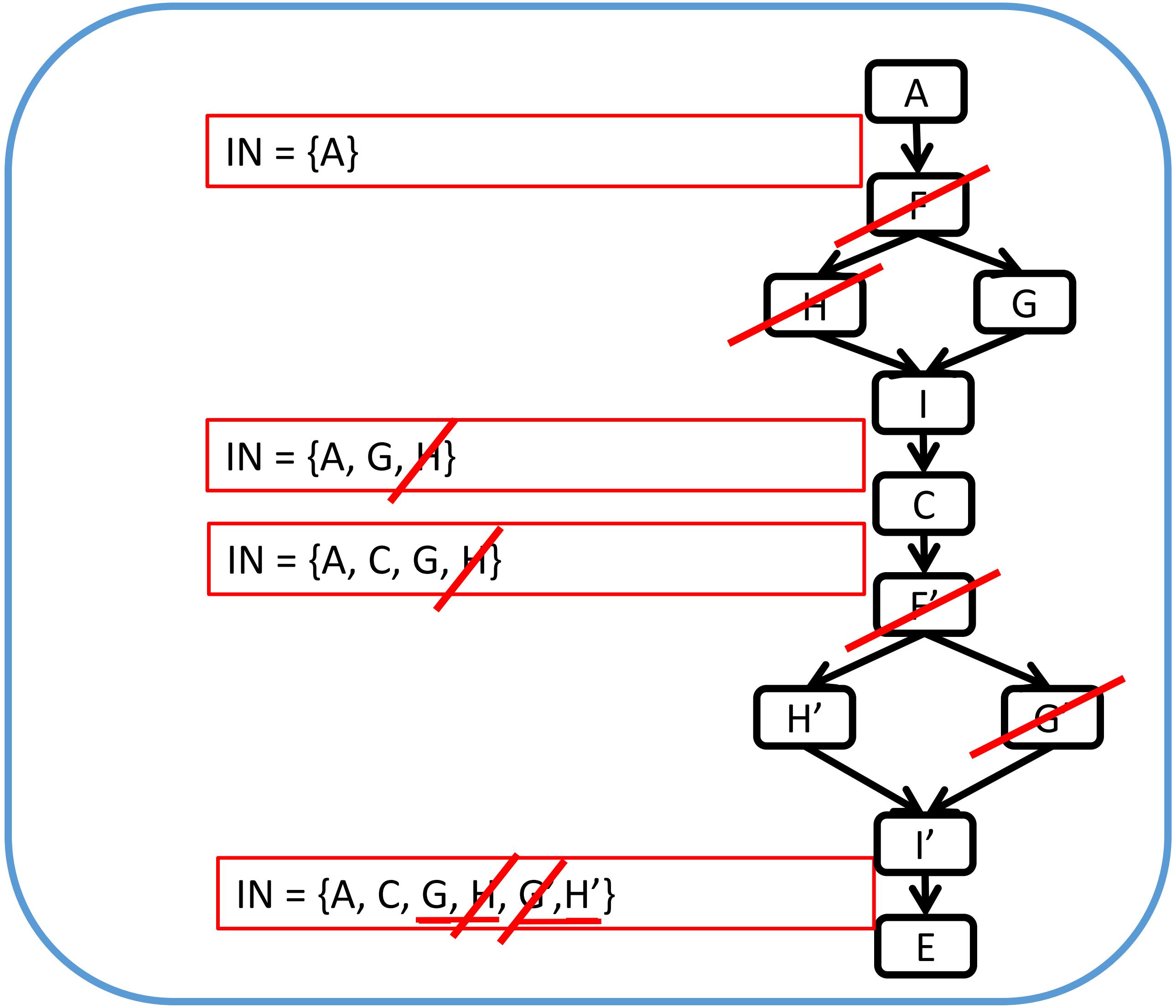
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:       m = 1;
      else
  H:       m = 2;
   I: return m;
}
```



Inter-procedural dataflow analysis flow/context-sensitive

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:       m = 1;
       else
  H:       m = 2;
   I: return m;
}
```



- What did it change?
- Solutions?

Function inlining

- Inlining
  - Use a new copy of a procedure's CFG at each call site
  - Useful if not used always

- Problems?
  - May be expensive! Exponential increase in size of CFG
  - You can't always determinate callee at compile time (e.g., in OO languages)
  - Library source is usually unavailable

- What about recursive procedures?

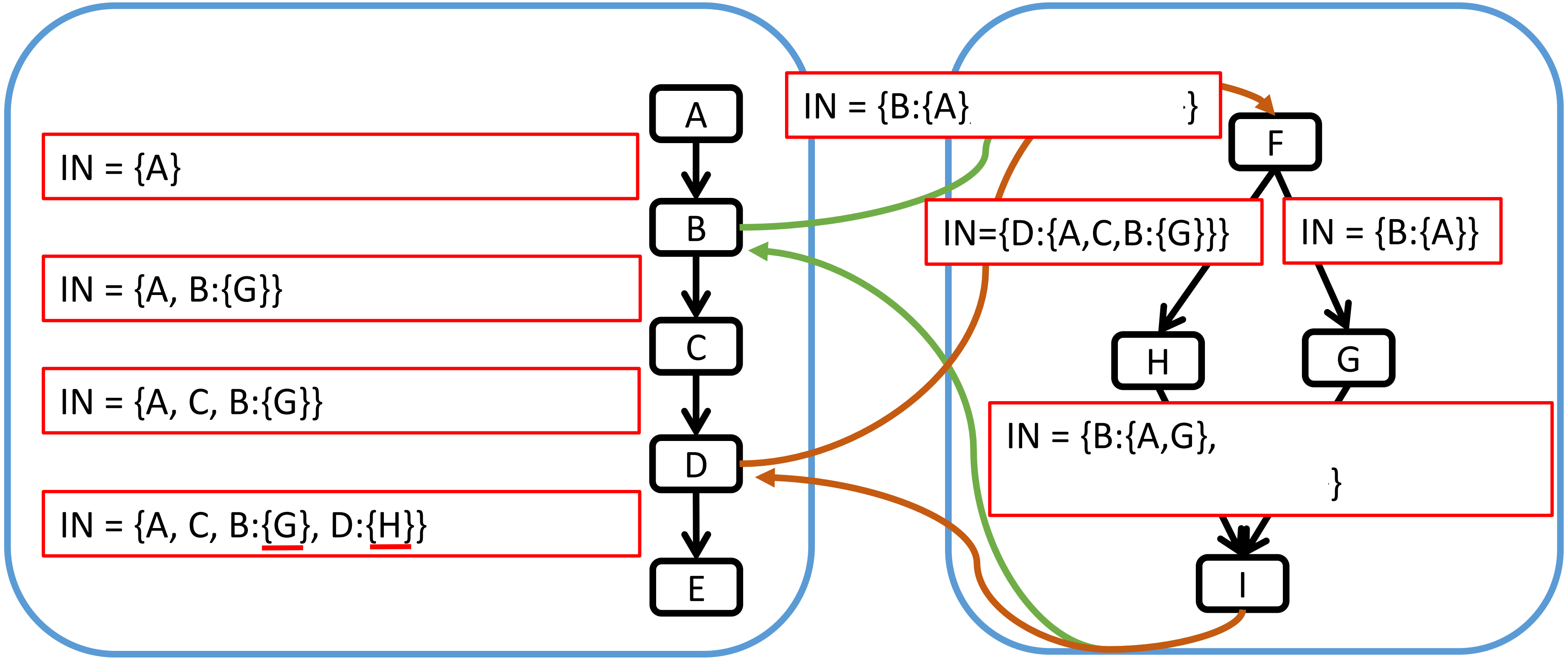
  p(int n) { … p(n-1); … }

- More generally, cycles in the call graph

Inter-procedural dataflow analysis flow/context/path-sensitive

- Better accuracy
- Much worst analysis time

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
      else
  H:      m = 2;
   I: return m;
}
```

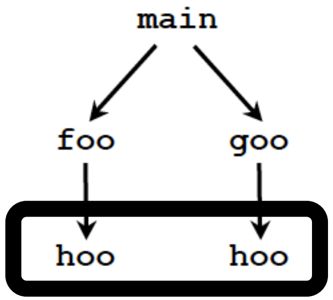


Inter-procedural dataflow analysis flow/context-sensitive

What about programs with a deep hierarchy of many procedures?

Re-analyze callee for all distinct calling paths

- Pro: precise
- Cons: what's the analysis time?
- Solution: separate compilation

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 D: t = p(y);
 E: print t, r;
}
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  F: if (v < 10)
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}
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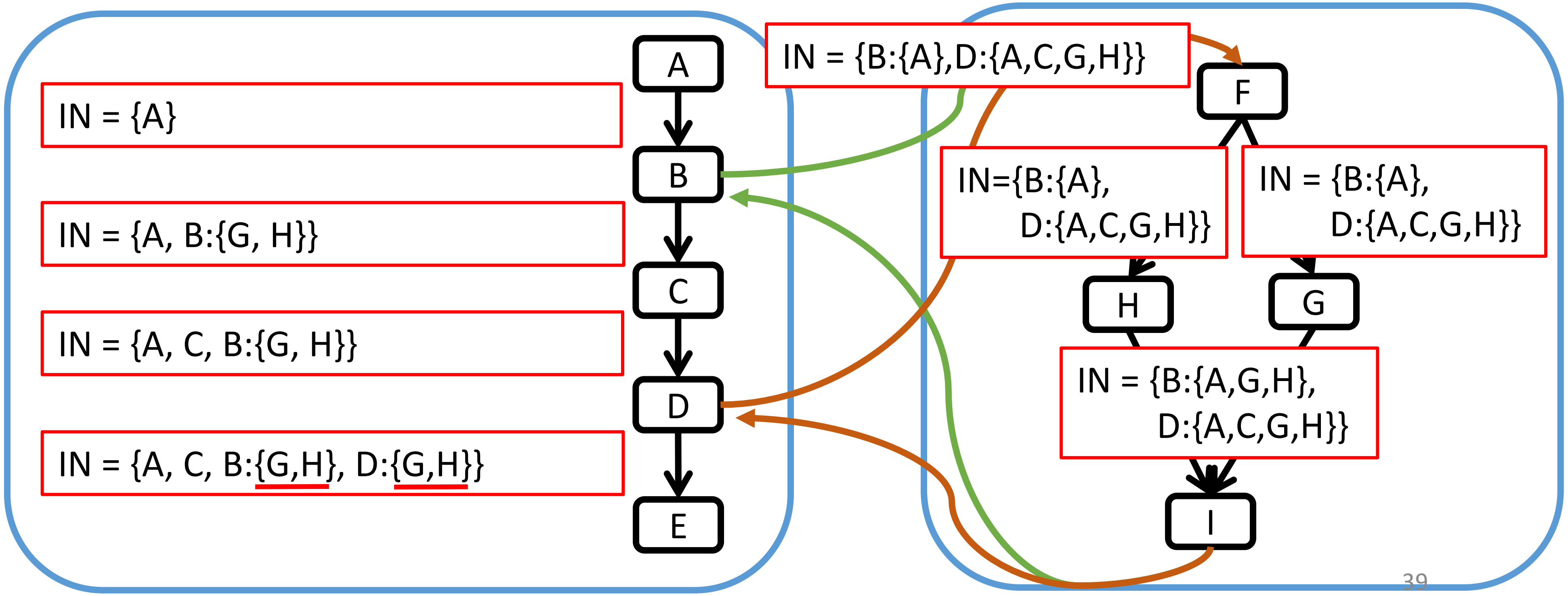

Outline

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⑤ Final remarks

Separate compilation

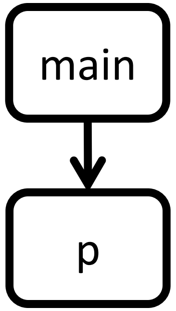
- Each function is analyzed separately
- The result of the analysis of a function is a “summary node”, which reports what you need to know about this function
- When you analyze a function F that invokes G, you use the summary node of G to analyze F
- Typically: the call graph is used to first analyze callees and then callers

Summary context: example

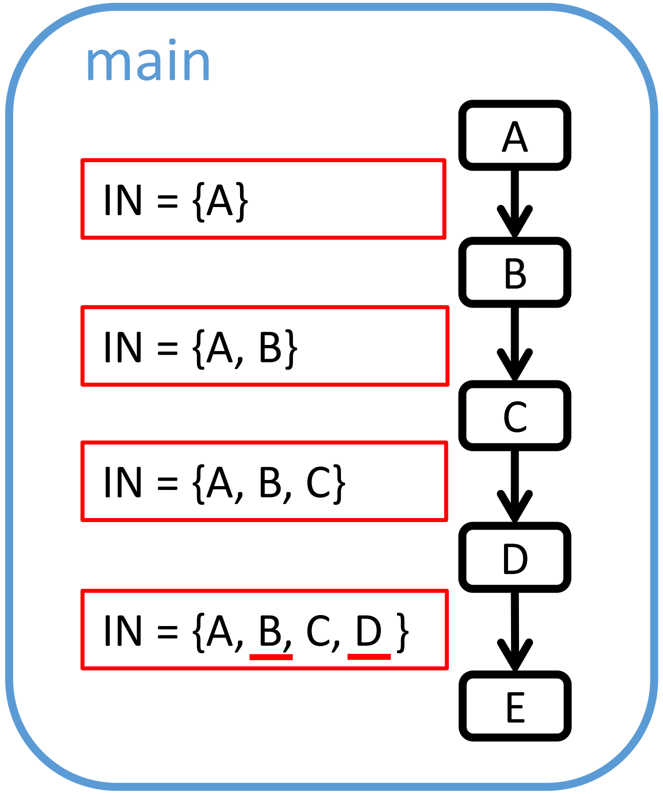
- Summary context: summarize effect of called procedure for callers

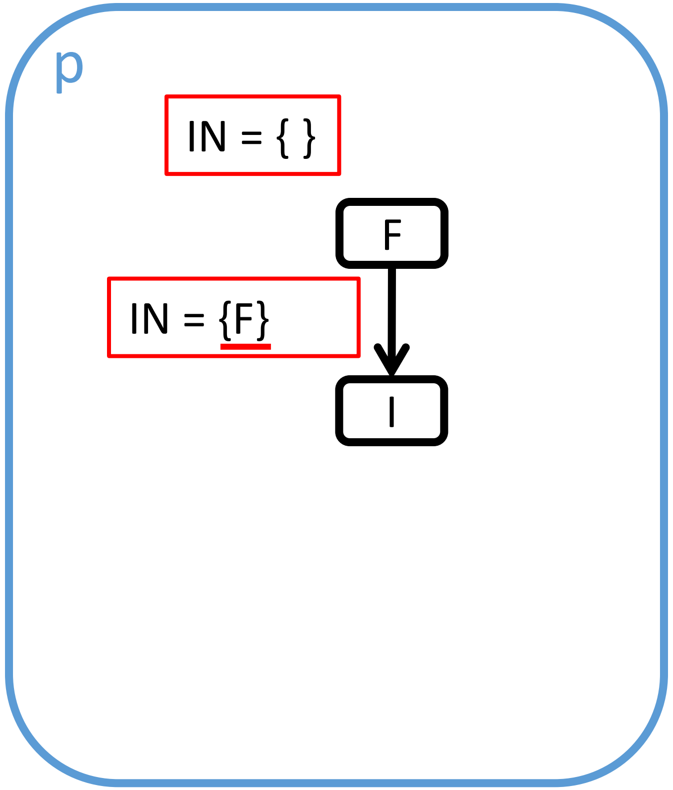
main() {
A: x = 7;
B: r = p(x);
C: y = 80;
D: t = p(y);
E: print ~~t~~, ~~r~~;
}   42   42

int p (int v) {
F: int v = 42;
I: return v;
}



Higher accuracy compared to intra-procedural





Summary: p returns 42

Summary context: example

- Summary context: summarize effect of called procedure for callers

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
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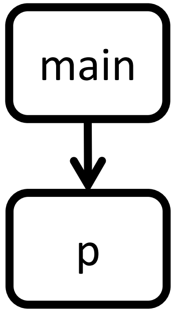
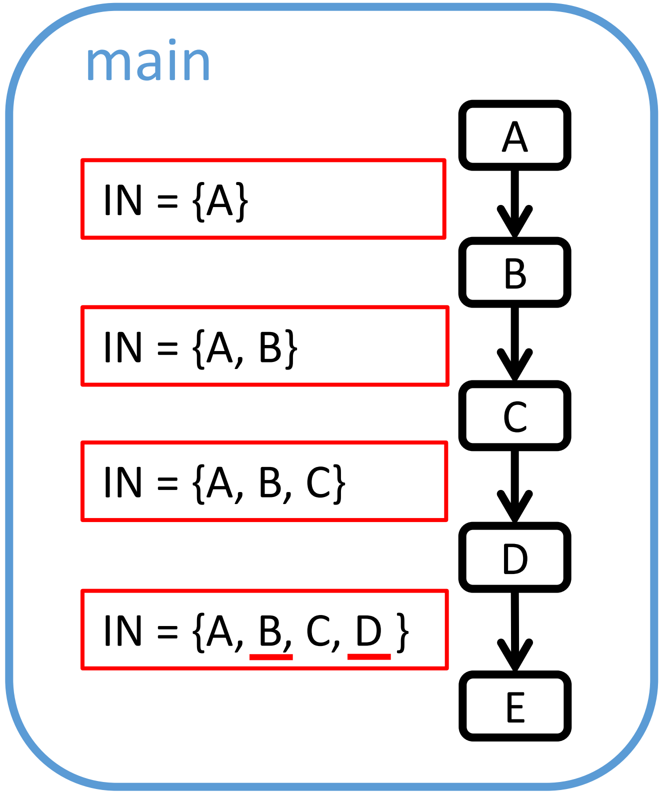
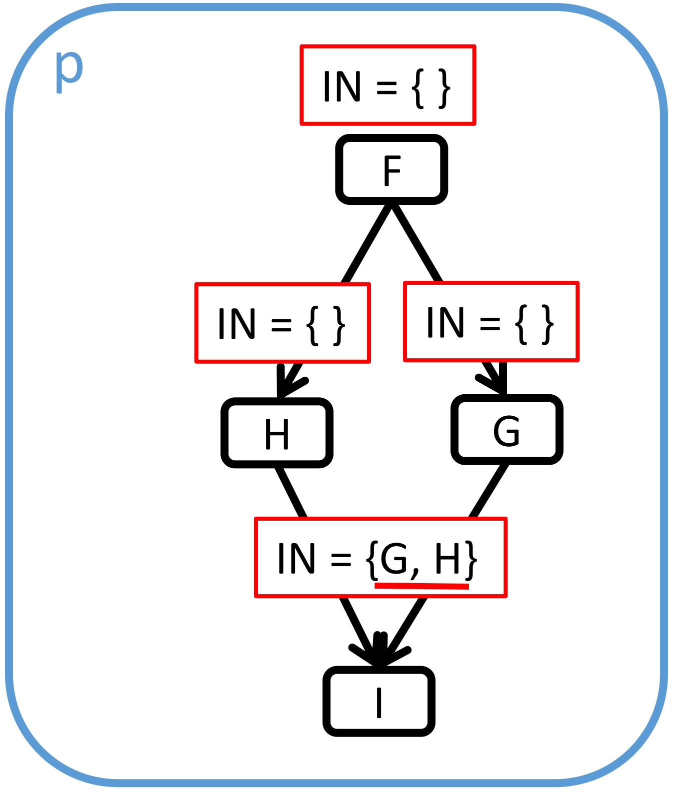






Summary: p doesn't return a constant

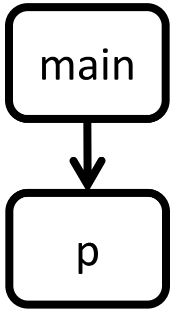
Separate compilation

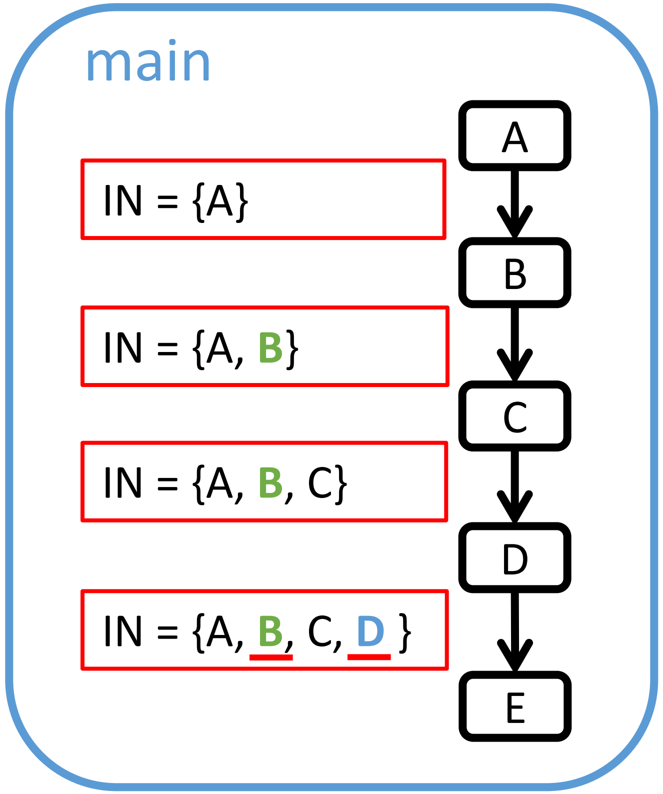
- Each function is analyzed separately
- The result of the analysis of a function is a “summary node”, which reports what you need to know about this function
- We can decide to increase the amount of information embedded in the summary node

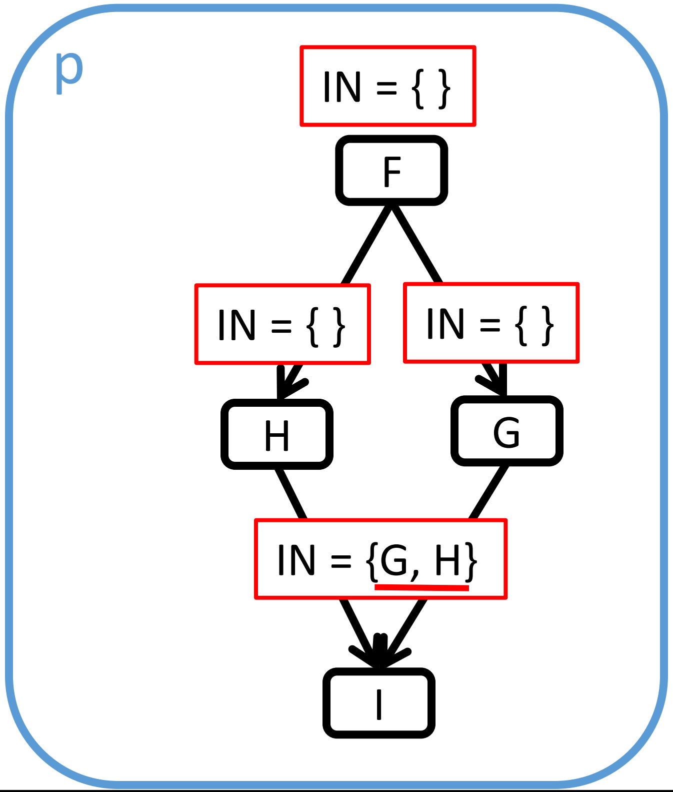
Summary context: example 2

- Summary context: summarize effect of called procedure depending on formal parameters for callers

main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print ~~t~~, ~~r~~;
}   2   1
int p (int v) {
 F: if (v < 10)
 G: m = 1;
   else
 H: m = 2;
 I: return m;
}

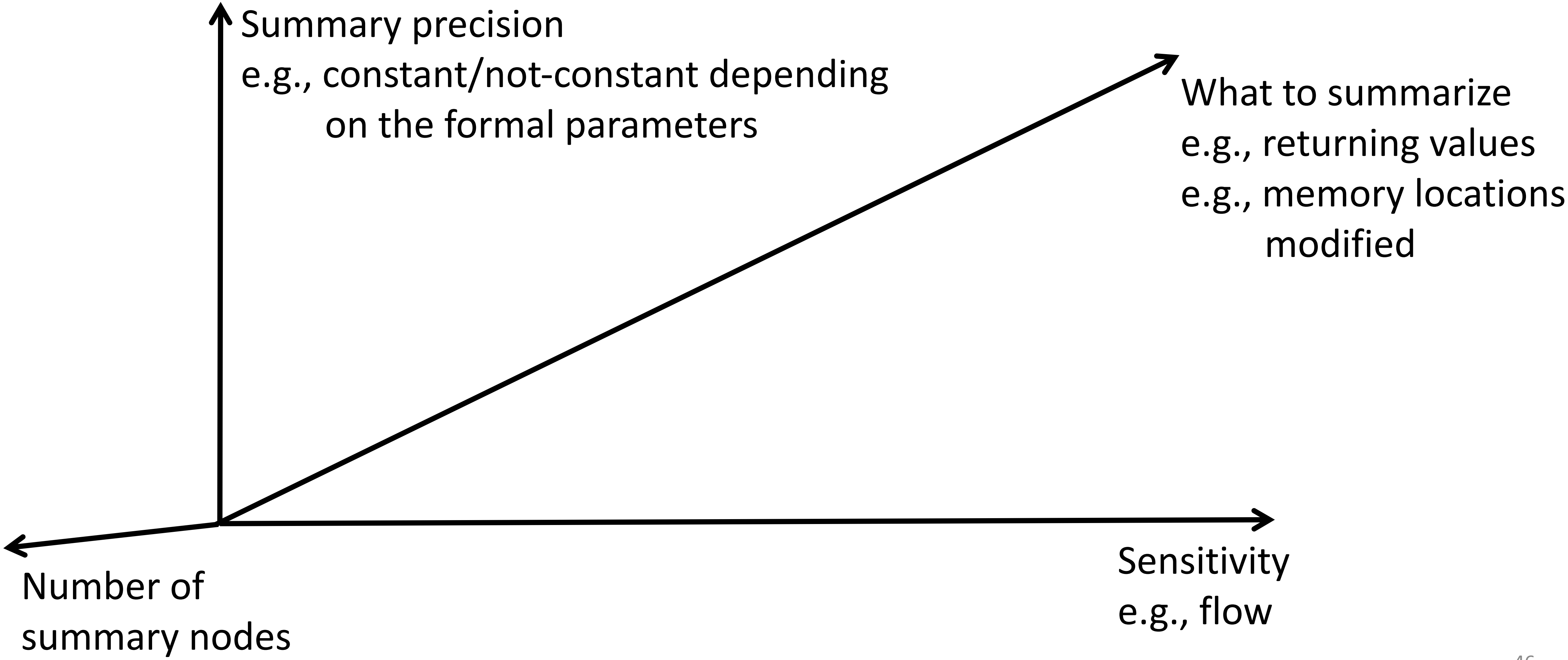






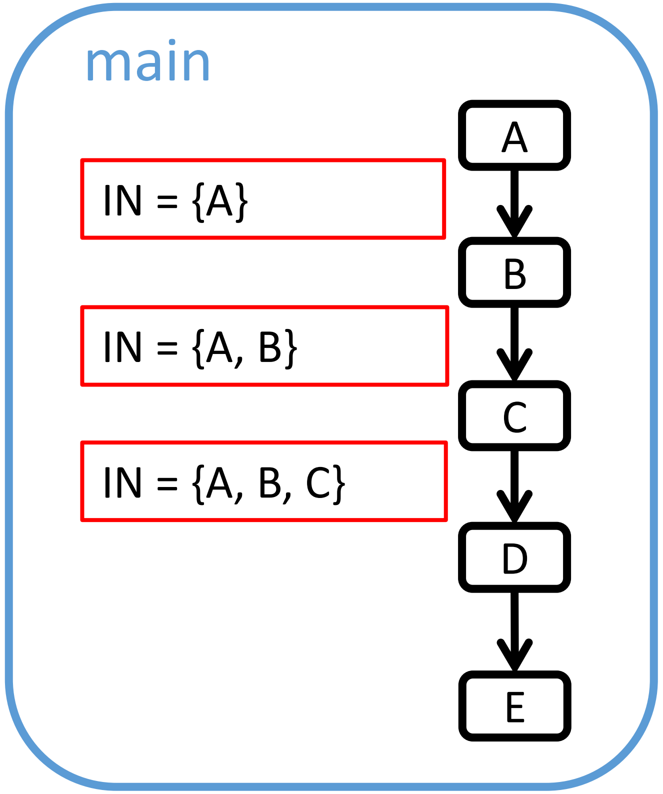
Summary: p returns
Constant 1 if parameter is < 10
Constant 2 otherwise

Designing an inter-procedural analysis

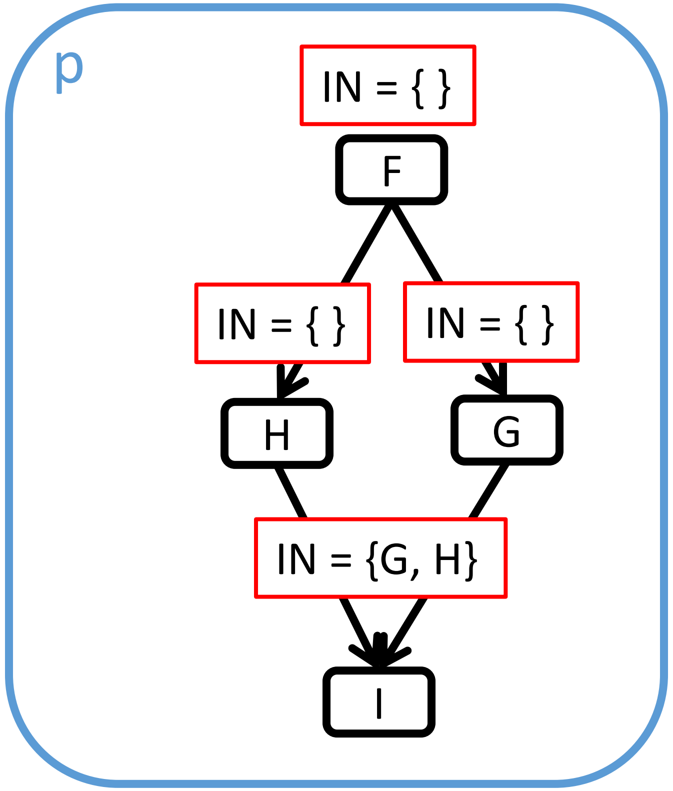


Context sensitivity

- Simplest solution: 1 copy per procedure



- Do we have a summary node for p?
- No. Compute it

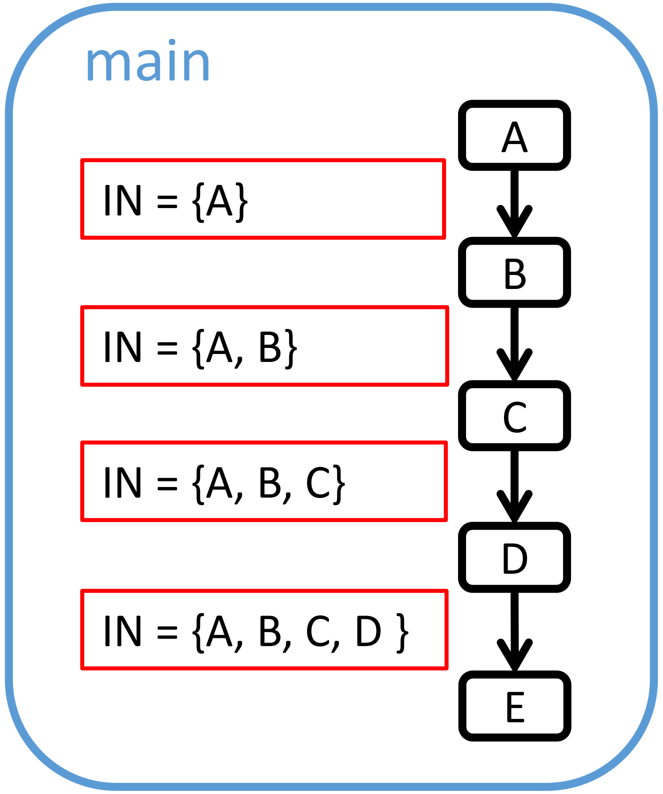


Summary: p doesn't return a constant

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
        else
  H:      m = 2;
   I: return m;
}
```

Context sensitivity

- Simplest solution: 1 copy per procedure



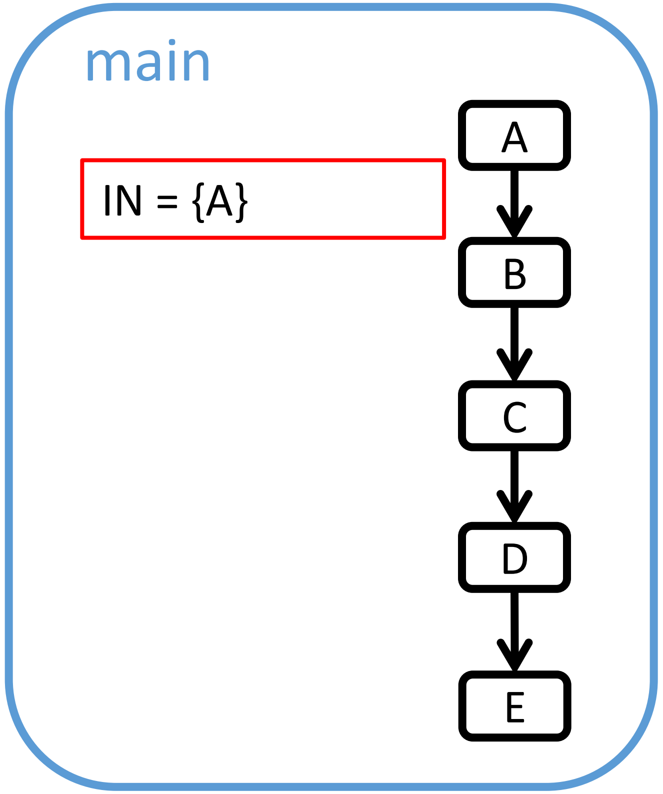
Summary: p doesn’t return a constant

- Do we have a summary node for p?
- Yes. Fetch it

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
      else
  H:      m = 2;
   I: return m;
}
```

Context sensitivity

- Simplest solution: 1 copy per procedure
- Simple solution: make a small number of copies of contexts (e.g., all callees of a procedure from a caller)

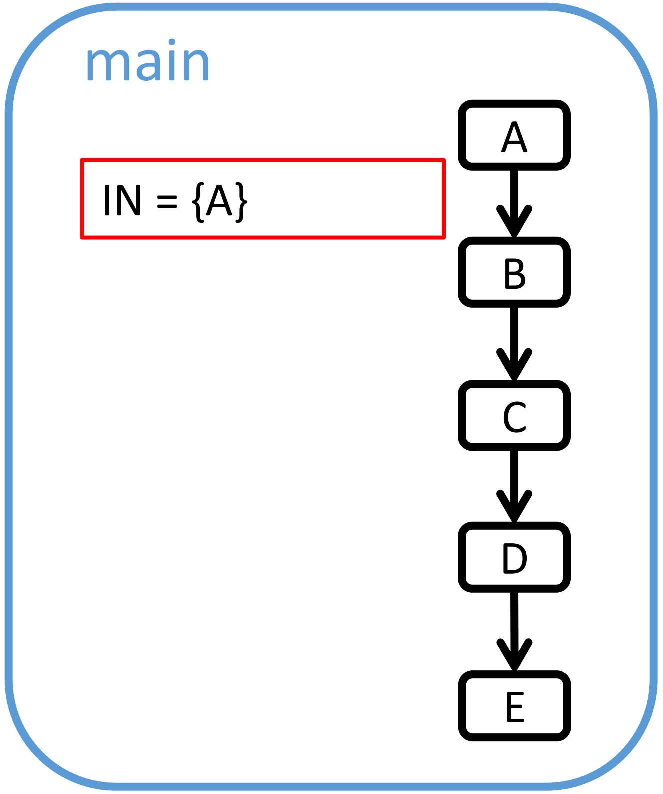


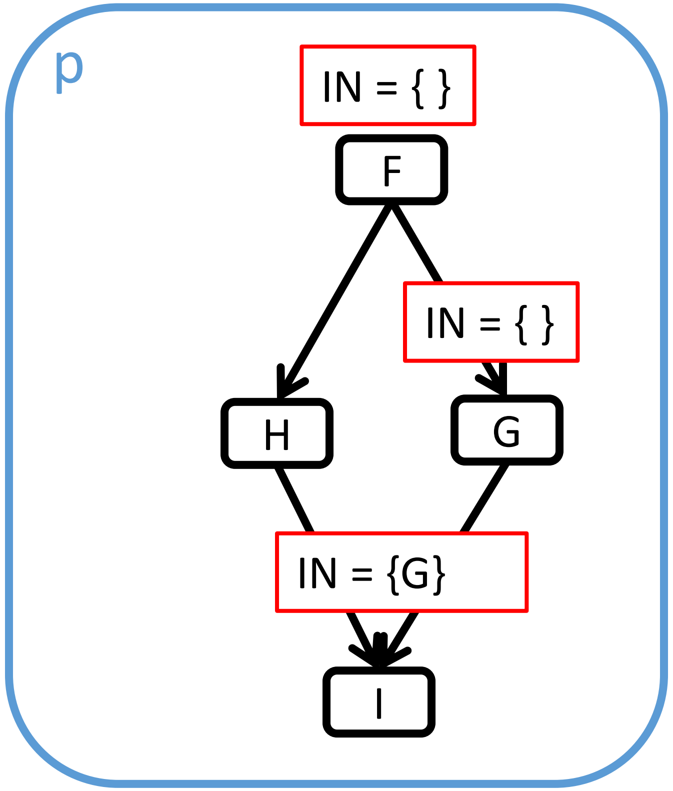
- Do we have a summary node for p(7)?
- No. Compute it

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
      else
  H:      m = 2;
   I: return m;
}
```

Context sensitivity

- Simplest solution: 1 copy per procedure
- Simple solution: make a small number of copies of contexts (e.g., all callees of a procedure from a caller)



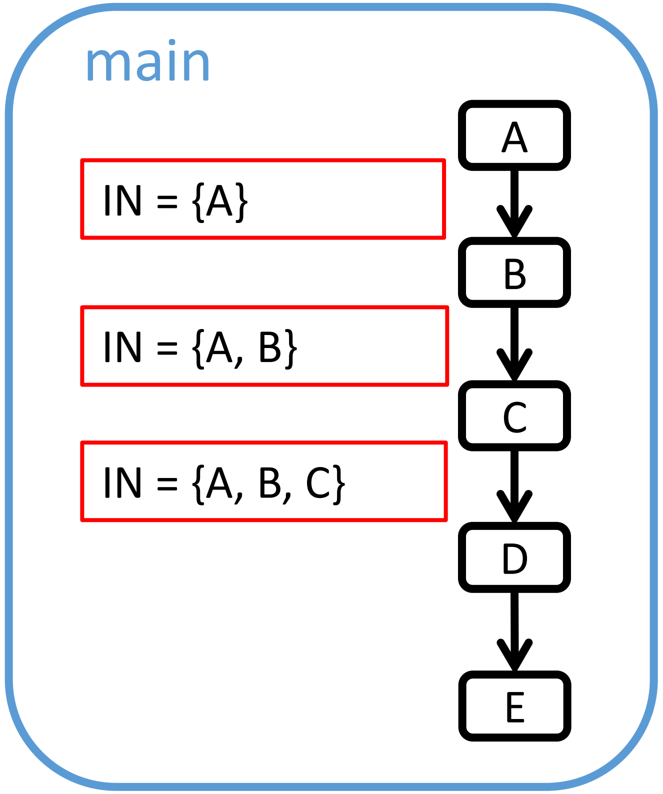



```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
        else
  H:      m = 2;
   I: return m;
}
```

Context sensitivity

Summary: p(7) returns 1

- Simplest solution: 1 copy per procedure
- Simple solution: make a small number of copies of contexts (e.g., all callees of a procedure from a caller)



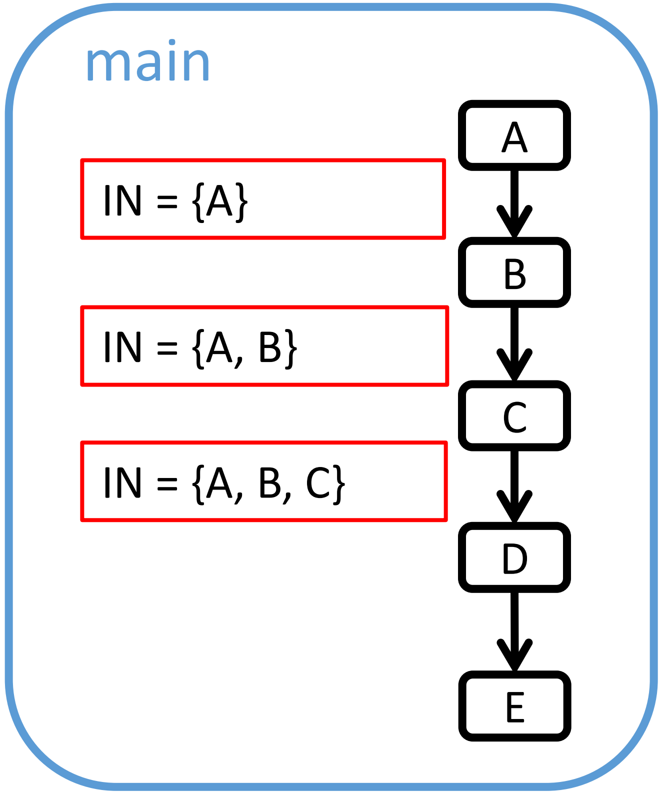
- Do we have a summary node for p(80)?
- No. Compute it

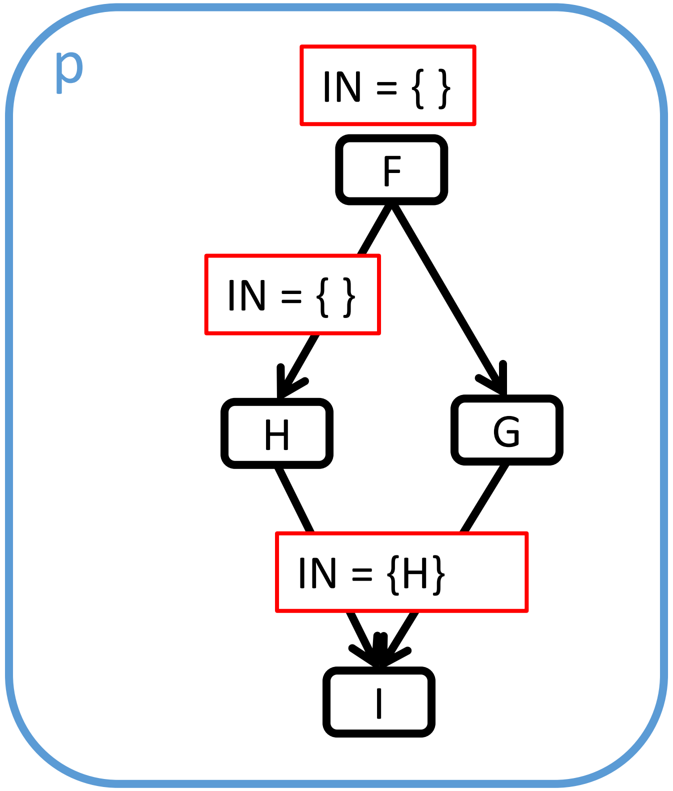
```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:       m = 1;
        else
  H:       m = 2;
   I: return m;
}
```

Context sensitivity

Summary: p(7) returns 1

- Simplest solution: 1 copy per procedure
- Simple solution: make a small number of copies of contexts (e.g., all callees of a procedure from a caller)



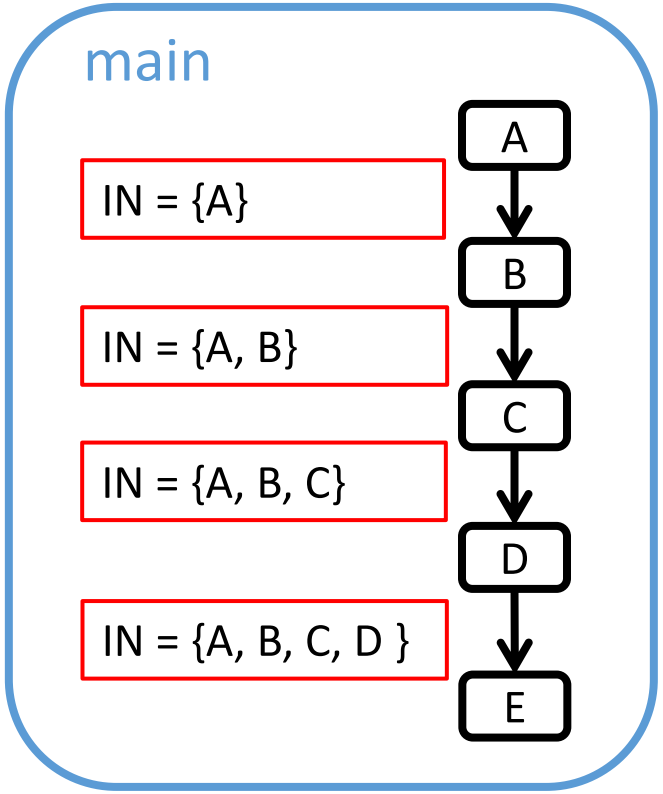



```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
          else
  H:      m = 2;
   I: return m;
}
```

Context sensitivity

Summary: p(7) returns 1
p(80) returns 2

- Simplest solution: 1 copy per procedure
- Simple solution: make a small number of copies of contexts (e.g., all callees of a procedure from a caller)



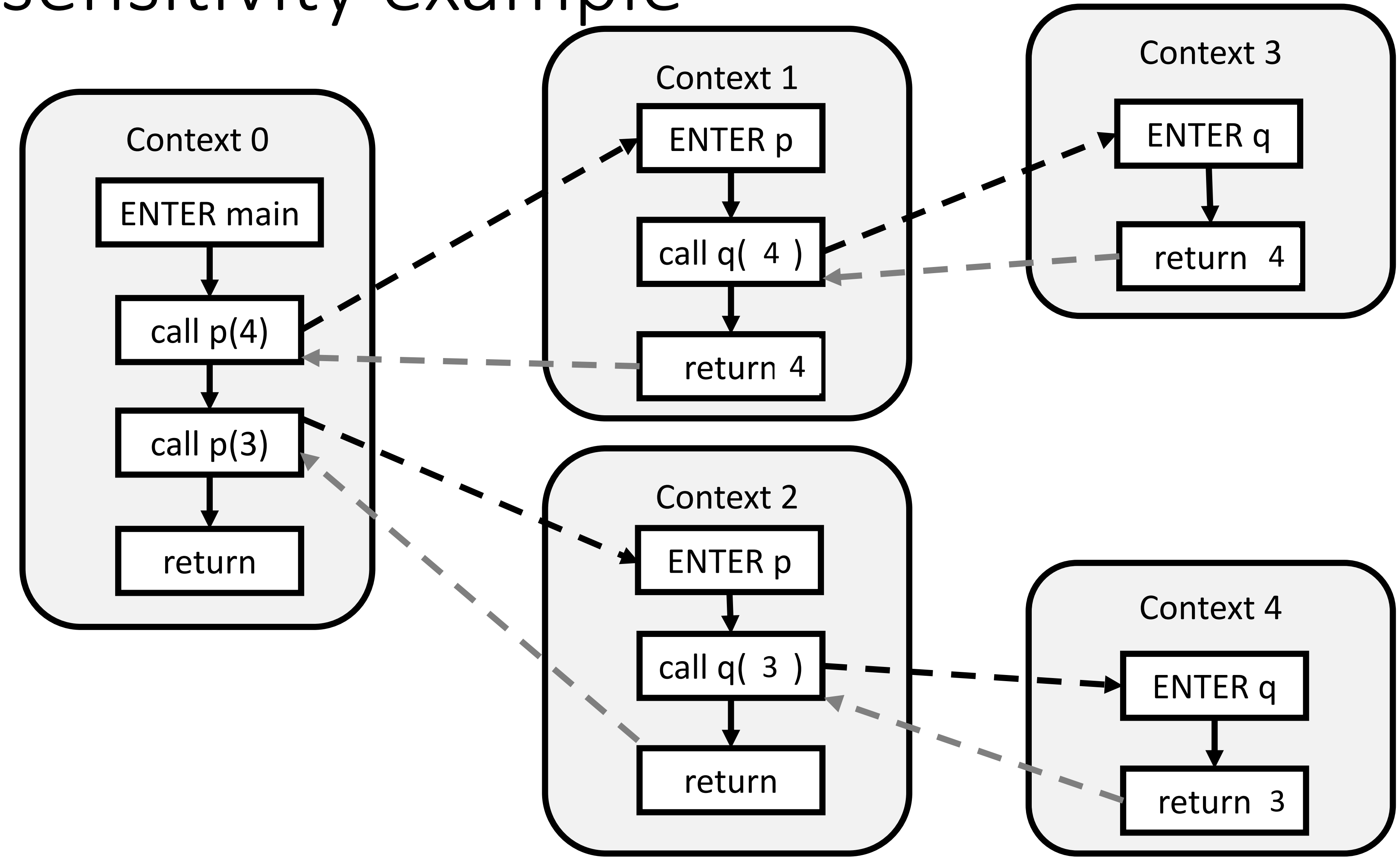

```
main() {
 A: x = 7;
 B: r = p(x);
 C: y = 80;
 D: t = p(y);
 E: print t, r;
}
int p (int v) {
  F: if (v < 10)
  G:      m = 1;
      else
  H:      m = 2;
   I: return m;
}
```

Context sensitivity

- Simplest solution: 1 copy per procedure
- Simple solution: make a small number of copies of contexts (e.g., all callees of a procedure from a caller)
- Advanced solutions: use context information to determine when to share a copy
- Choice of what to use for context will produce different tradeoffs between precision and scalability
- Common choice: approximation of call stack

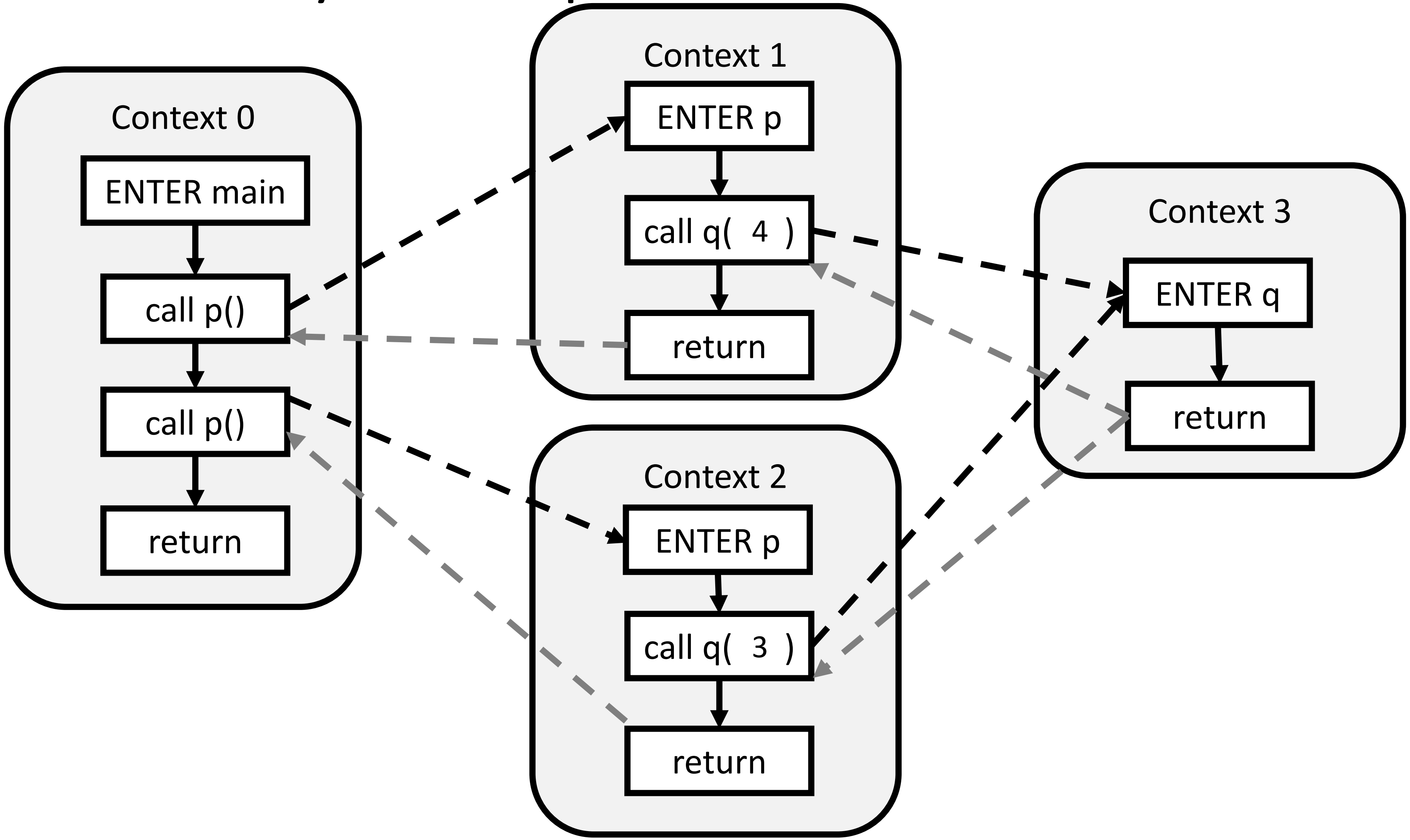
Context sensitivity example

```
main() {
 1: int v =p(4);
 2: v += p(3);
}
p (int f) {
 3:  return q(f)
}
q(int f){
  4: return f;
}
```



Context sensitivity example

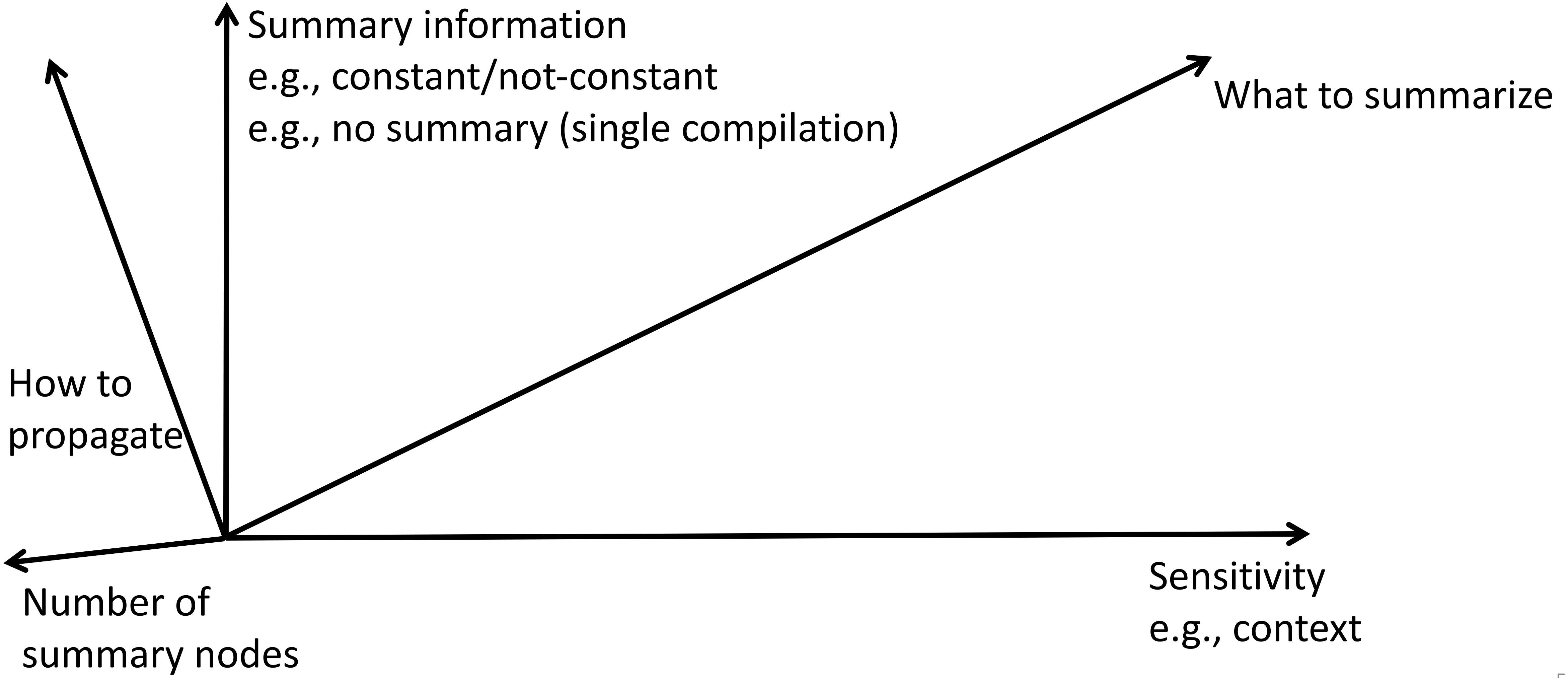
```
main() {
 1: p();
 2: p();
}
p () {
 3: q()
}
q(){
  4: return;
}
```



Other contexts

- Context sensitivity distinguishes between different calls of the same procedure
  - Choice of contexts determines which calls are differentiated
- Other choices of context are possible
  - Caller stack
    - Less precise than call-site stack
    - E.g., context “2::2” and “2::3” would both be “fib::fib”
- Object sensitivity: which object is the target of the method call?
  - For OO languages
  - Maintains precision for some common OO patterns
  - Requires pointer analysis to determine which objects are possible targets
  - Can use a stack (i.e., target of methods on call stack)

Designing an inter-procedural analysis



Outline

① Sensitivity of analysis

② Single compilation

③ Separate compilations

④ Caller -> callee vs. callee -> caller propagations

⑤ Final remarks

Inter-procedural analysis

- What to propagate through the call graph
- How to propagate through the call graph
- Example

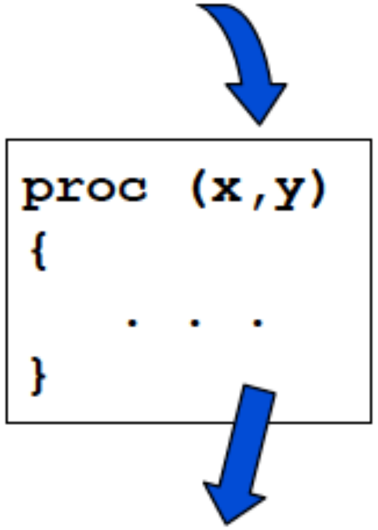
Two types of information

- Track information that flows into a procedure
  - Also known as **propagation** problems

  e.g., What formals are constant?

  e.g., Which formals are aliased to globals?

Summary: p(7) returns 1
p(80) returns 2



- Track information that flows out of a procedure
  - Also known as **side effect** problems

  e.g., Which globals are def'd/used by a procedure?

  e.g., Which locals are def'd/used by a procedure?

  e.g., Which actual parameters are def'd by a procedure?

Summary: p modifies
Global @X if parameter is < 10

Summary examples

- Propagation Summaries
  - MAY-ALIAS: The set of formals that may be aliased to globals and each other
  - MUST-ALIAS: The set of formals that are definitely aliased to globals and each other
  - CONSTANT: The set of formals that must be constant
- Side-effect Summaries
  - MOD: The set of variables possibly modified (defined) by a call to a procedure
  - REF: The set of variables possibly read (used) by a call to a procedure
  - KILL: The set of variables that are definitely killed by a procedure (e.g., in the liveness sense)

Inter-procedural analysis

- What to propagate through the call graph
- How to propagate through the call graph
- Example

Computing inter-procedural summaries

- Top-down (from callers to callees)
  - Summarize information about the caller (MAY-ALIAS, MUST-ALIAS)
  - Use this information inside the procedure body

```
int a;
void foo(int &b, &c){
  . . .
}
foo(a,a);
```

- Bottom-up (from callees to callers)
  - Summarize the effects of a call (MOD, REF, KILL)
  - Use this information around procedure calls

```
x = 7;
foo(x);
y = x + 3;
```

Bi-directional inter-procedural summaries

- Inter-procedural Constant Propagation (ICP)
  - Information flows from caller to callee and back

```
int a, b, c, d;
void foo(e){
    a = b + c;
    d = e + 2;
}
foo(3);
```

The calling context tells us that the formal e is bound to the constant 3, which enables constant propagation within foo()
After calling foo() we know that the constant 5 (3+2) propagates to the global d

- Inter-procedural Alias Analysis
  - Forward propagation: aliasing due to reference parameters
  - Side-effects: points-to relationships due to multi-level pointers

Inter-procedural analysis

- What to propagate through the call graph
- How to propagate through the call graph
- Example

Example: identify functions that might be affected by randomness

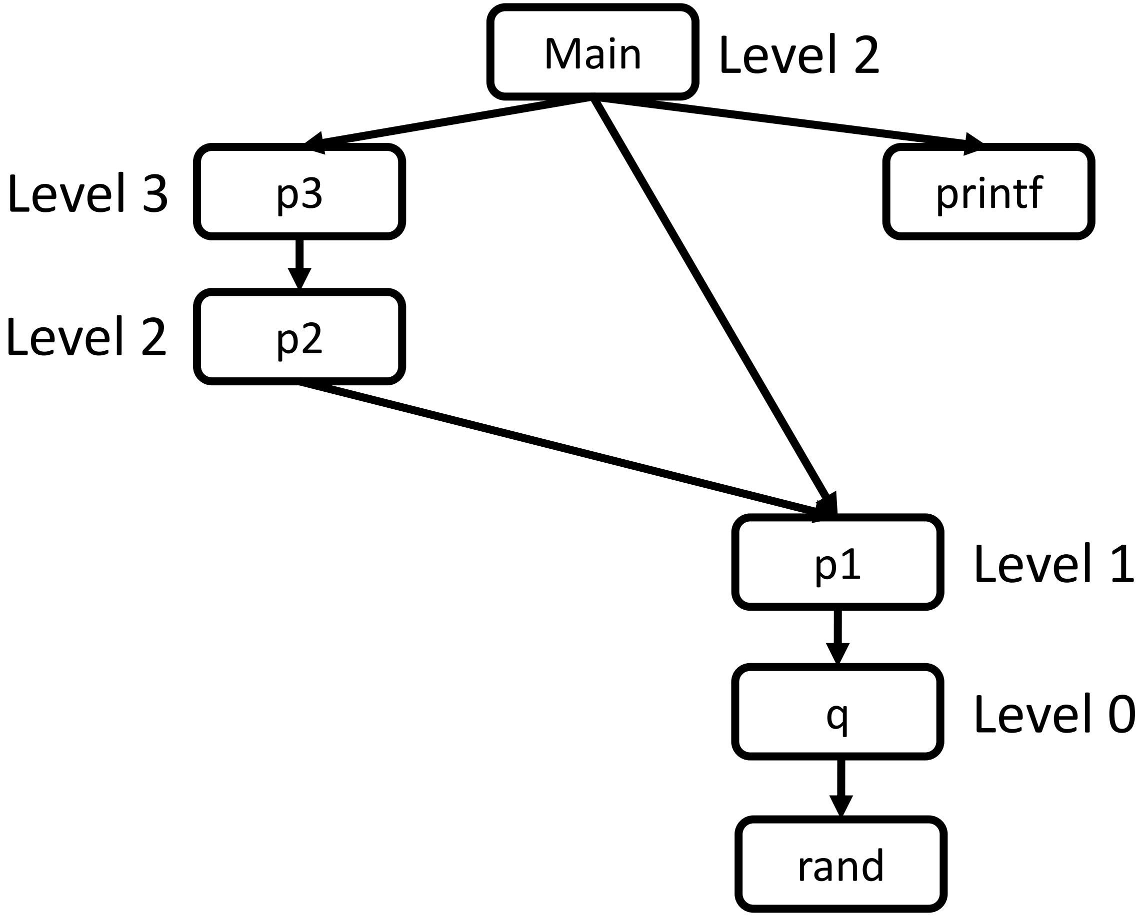
Problem:
Identify functions that might directly or indirectly invoke rand()

Output:
The set of functions affected by rand() and the length of the shortest path in the call graph to an invocation to rand().

How can we do it?

You can find the solution shown in the next slides here: LLVM_callgraph

Example: identify functions that might be affected by rand()




```c
int q (void){
  return rand() % 10;
}

int p1 (void){
  return q();
}

int p2 (void){
  return p1();
}

int p3 (void){
  return p2();
}

int main (int argc, char *argv[]){
  int t = p3();

  int r = p1();

  printf("%d %d\n", r, t);

  return 0;
}
```

Example: identify functions that might be affected by rand()

Functions affected:

- Level 0: q
- Level 1: p1
- Level 2: p2
- Level 2: main
- Level 3: p3

Functions not affected:

```c
int q (void){
  return rand() % 10;
}

int p1 (void){
  return q();
}

int p2 (void){
  return p1();
}

int p3 (void){
  return p2();
}

int main (int argc, char *argv[]){
  int t = p3();

  int r = p1();

  printf("%d %d\n", r, t);

  return 0;
}
```

Example: identify functions that might get affected by rand()

Data structures:

```
enum randomUses {TBC, invoked, notInvoked};
struct random_info_t {
  randomUses r;
  uint32_t level;
};
```

Summary

```
std::map<Function *,random_info_t> randomInfo;
```

Example: identify functions that might get affected by rand()

```
void printStatus (Module &M){
  errs() << "   Functions affected:\n";
  for (auto &F : M) {
    if (randomInfo[&F].r == invoked){
      errs() << "    Level " << randomInfo[&F].level << ": " << F.getName() << "\n";
    }
  }

  errs() << "   Functions not affected:\n";
  for (auto &F : M) {
    if (randomInfo[&F].r == notInvoked){
      errs() << "     " << F.getName() << "\n";
    }
  }

  return ;
}
```

Functions affected:

- Level 0: q
- Level 1: p1
- Level 2: p2
- Level 3: p3
- Level 2: main

Functions not affected:

Example: identify functions that might get affected by rand()

```
bool runOnModule(Module &M) override {
  errs() << "Module \"" << M.getName() << "\"\n";

  errs() << " Identify functions affected directly\n" ;
  tagFunctionsDirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions affected indirectly\n" ;
  identifyFunctionsIndirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions not affected\n" ;
  identifyFunctionsNotAffected(M);
  printStatus(M);

  return false;
}
```

Intra-procedural analysis

Inter-procedural analysis

Example: identify functions that might get affected by rand()

```
bool runOnModule(Module &M) override {
  errs() << "Module \"" << M.getName() << "\"\n";

  errs() << " Identify functions affected directly\n" ;
  tagFunctionsDirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions affected indirectly\n" ;
  identifyFunctionsIndirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions not affected\n" ;
  identifyFunctionsNotAffected(M);
  printStatus(M);

  return false;
}
```

Example: identify functions that might get affected by rand()

```
void tagFunctionsDirectlyAffected (Module &M){
  for (auto &F : M) {

    /* Initialize the information about F.
     */
    randomInfo[&F].r = TBC;
    randomInfo[&F].level = 0;

    /* Analyze F.
     */
    for (auto &B : F) {
      for (auto &I : B) {
        if (auto call = dyn_cast<CallInst>(&I)){
-  9 lines: Analyze a call instruction included in F.
        }
      }
    }
  }

  return ;
}
```

```
/* Analyze a call instruction included in F.
 */
Function *callee = call->getCalledFunction();
if (   (callee == NULL)                    ||
       (callee->getName() == "rand") ){
  randomInfo[&F].r = invoked;
  randomInfo[&F].level = 0;
}
```

Example: identify functions that might get affected by rand()

```
bool runOnModule(Module &M) override {
  errs() << "Module \"" << M.getName() << "\"\n";

  errs() << " Identify functions affected directly\n" ;
  tagFunctionsDirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions affected indirectly\n" ;
  identifyFunctionsIndirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions not affected\n" ;
  identifyFunctionsNotAffected(M);
  printStatus(M);

  return false;
}
```

Example: identify functions that might get affected by rand()

```
void identifyFunctionsIndirectlyAffected (Module &M){
  bool changed;
  do {
    changed = false;

    for (auto &F : M) {
      if (randomInfo[&F].r != invoked){
        continue ;
      }

20 lines: for (auto &U : F.uses()){----------------------
    }

  } while (changed);

  return ;
}
```

```
for (auto &U : F.uses()){
  auto user = U.getUser();
  if (auto callInst = dyn_cast<Instruction>(user)){
    auto caller = callInst->getFunction();
    switch (randomInfo[caller].r){
      case TBC:
        randomInfo[caller].r = invoked;
        randomInfo[caller].level = randomInfo[&F].level + 1;
        changed = true;
        break ;

      case invoked:
        if (randomInfo[caller].level > (randomInfo[&F].level + 1)){
          randomInfo[caller].level = randomInfo[&F].level + 1;
          changed = true;
        }
        break ;
    }
  }
}
```

Example: identify functions that might get affected by rand()

```
bool runOnModule(Module &M) override {
  errs() << "Module \"" << M.getName() << "\"\n";

  errs() << " Identify functions affected directly\n" ;
  tagFunctionsDirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions affected indirectly\n" ;
  identifyFunctionsIndirectlyAffected(M);
  printStatus(M);

  errs() << " Identify functions not affected\n" ;
  identifyFunctionsNotAffected(M);
  printStatus(M);

  return false;
}
```

Example: identify functions that might get affected by rand()

```
void identifyFunctionsNotAffected (Module &M){
  for (auto &F : M) {
    if (  (!F.empty())                &&
          ( randomInfo[&F].r == TBC)  ){
      randomInfo[&F].r = notInvoked;
    }
  }

  return ;
}
```

Computing inter-procedural summaries

- Top-down
  - Summarize information about the caller (MAY-ALIAS, MUST-ALIAS)
  - Use this information inside the procedure body

```
int a;
void foo(int &b, &c){
  . . .
}
foo(a,a);
```

Is our pass Top-down or bottom-up?

- Bottom-up
  - Summarize the effects of a call (MOD, REF, KILL)
  - Use this information around procedure calls

```
x = 7;
foo(x);
y = x + 3;
```

Outline

① Sensitivity of inter-procedural analysis

② Single compilation

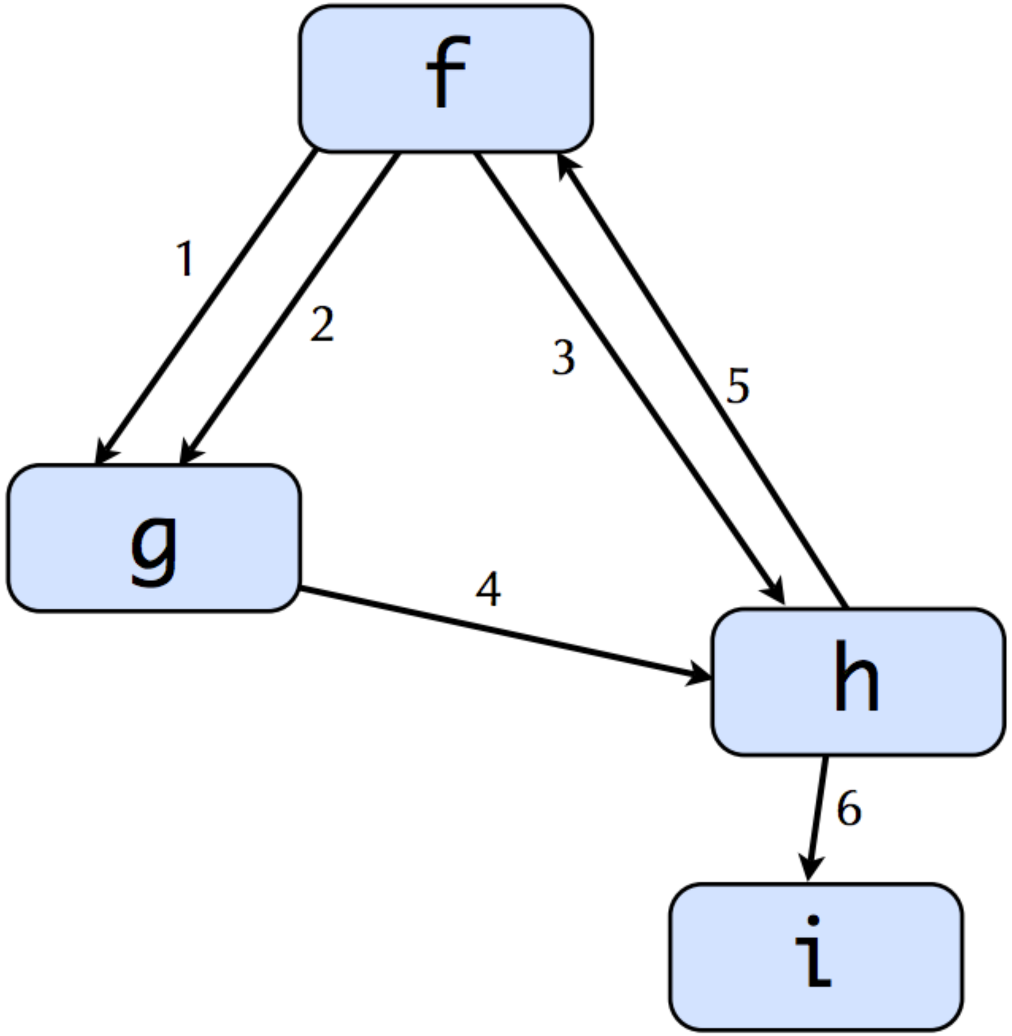
③ Separate compilations

④ Caller -> callee vs. callee -> caller propagations

⑤ Final remarks

What about cycles in the call graph?

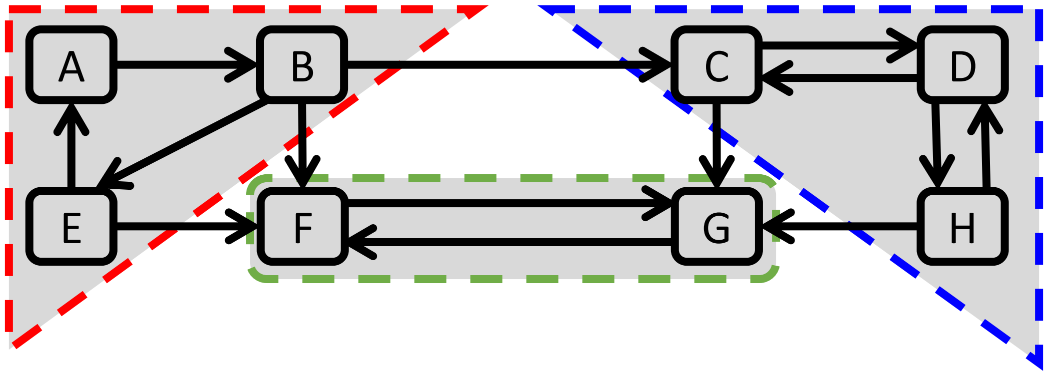
```
f() {
   1:  g();
   2:  g();
   3:  h();
}

g() {
   4: h();
}

h() {
   5: f();
   6: i();
}

i() { … }
```



Handling cycles in the call graph

- Long story short: iterate until a fixed point is reached
- It can take a while for naïve solutions …

- **Strongly connected components**:
  A directed graph is called strongly connected
  if there is a path in each direction
  between each pair of vertices of the graph



Handling cycles in the call graph

To reach the fixed point faster:

① Identify strongly-connected-components (SCC)

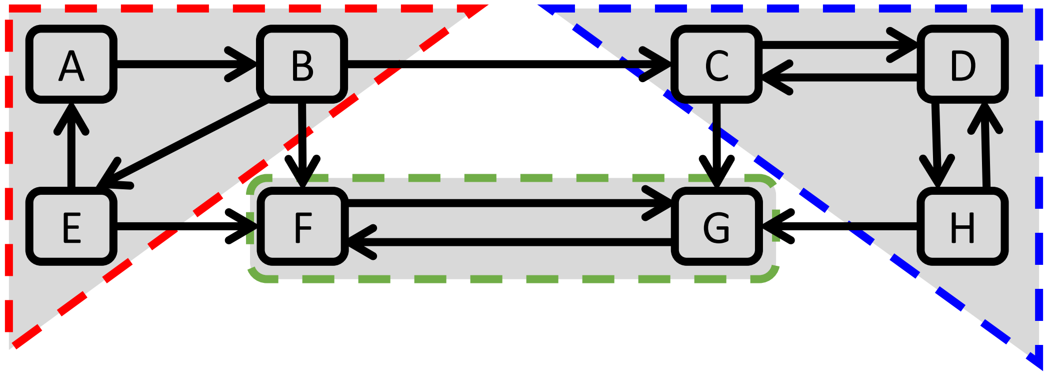
② do{

For each SCC in SCCs:

Iterate among functions within SCC

Iterate among every node in the call graph

} while (anyChange);



Indirect calls

```
void foo (int a, int (*p_to_f)(int
  int l = (*p_to_f)(5);
  a = l + 1;
  return a;
}
```

Is l constant?

- How can we identify indirect calls in LLVM?

```
bool runOnModule(Module &M) override {
  errs() << "Module \"" << M.getName() << "\"\n";
  for (auto &F : M) {
    errs() << " Function \"" << F.getName() << "\"\n";
    for (auto &B : F) {
        for (auto &I : B) {
            if (auto call = dyn_cast<CallInst>(&I)){
              Function *callee = call->getCalledFunction();
              if (callee == NULL){
                errs() << "   Calls a function indirectly\n";
                continue ;
              }
              errs() << "   Calls " << callee->getName() << "\n";
            }
        }
    }
  }

  return false;
}
```

Indirect calls

```
void foo (int a, int (*p_to_f)(int v)){
  int l = (*p_to_f)(5);
  a = l + 1;
  return a;
}
```

Is l constant?

- How can we identify indirect calls in LLVM?
- How can we handle indirect calls?

```
errs() << " Function \"" << F.getName() << "\"\n";
CallGraphNode *n = CG[&F];

for (auto callee : *n){
  auto calleeNode = callee.second;
  auto callInst = callee.first;

  auto calleeF = calleeNode->getFunction();
  if (calleeF == nullptr) continue ;
  errs() << "   \"" << calleeF->getName() << "\"";

  errs() << "  via call instruction \"" << *callInst << "\"\n";
}
```

Procedure cloning

- Step 1: clone a function
  - A new function is created that is the exact clone of another one with only one difference:
    The name of the clone function is different then the original function

```
void foo (){
    f(7)
    f(7)
}
```

```
void f (int p){
    int x = p + 3;
    …
}
```

Cloning

```
void f_2 (int p){
    int x = p + 3;
    …
}
```

Specialization

```
void f_2 (void){
    int x = 10;
    …
}
```

```
void foo (){
    f_2();
    f_2();
}
```

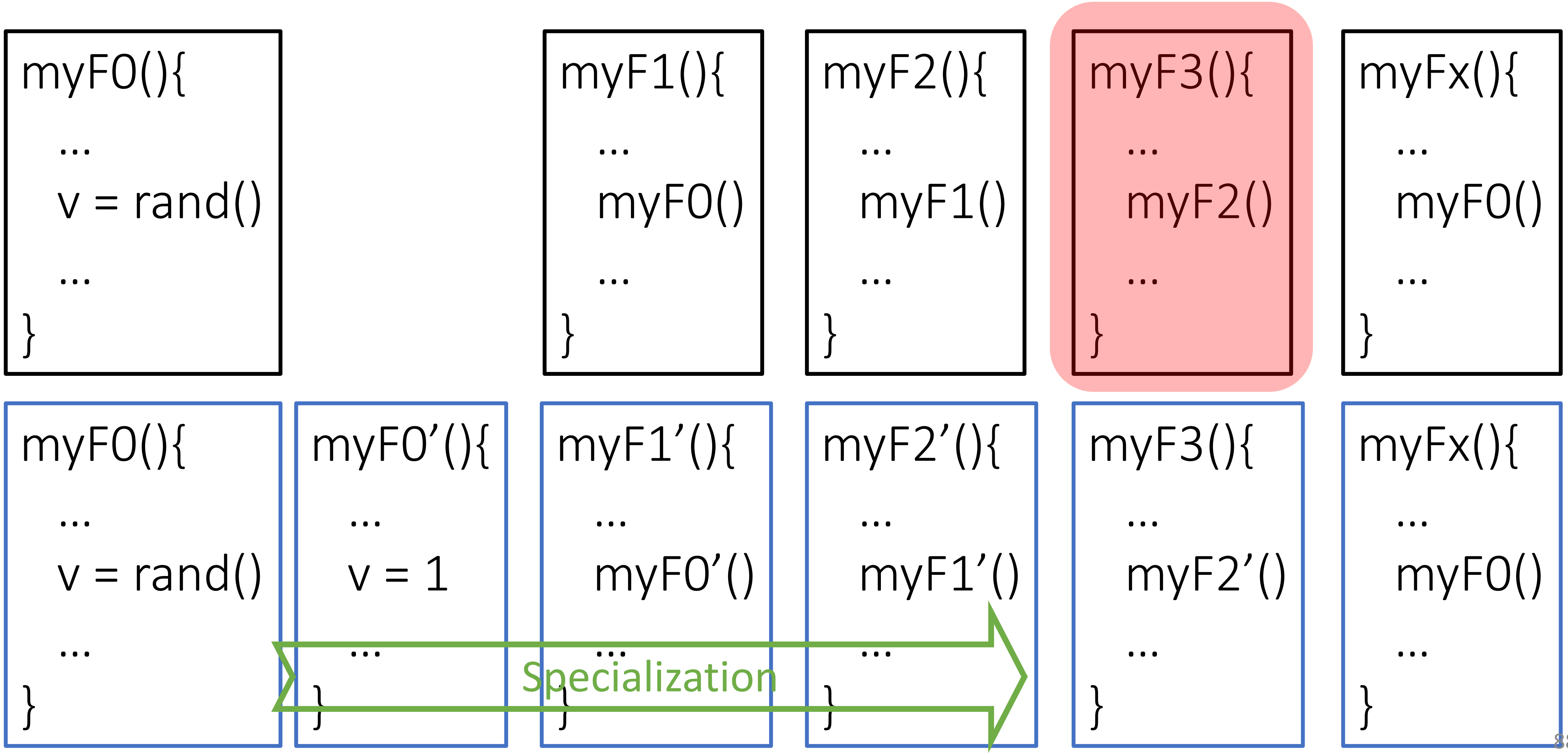
- Step 2: specialize the clone for a particular set of callers
  - Create a customized version of procedure for particular call sites
  - Compromise between inlining and inter-procedural optimization

Procedure cloning

- Pros
  - Less code bloat than inlining
  - Recursion is not an issue (as compared to inlining)
  - Better caller/callee optimization potential (versus inter-procedural analysis)

- Cons
  - Still some code bloat (versus inter-procedural analysis)
  - May have to do inter-procedural analysis anyway
    e.g. Inter-procedural constant propagation can guide cloning

Example: transform functions with level >=3 to be not affected by rand()



Example: transform functions with level >=3 to be not affected by rand()

```c
int q (void){
  return rand() % 10;
}
int p1 (void){
  return q();
}
int p2 (void){
  return p1();
}
int p3 (void){
  return p2();
}
int p4 (void){
  return p2() + p1();
}
int main (int argc, char *argv[]){
  int t = p3();
  int r = p1();
  printf("%d\n", t + r + p4());
  return 0;
}
```

Ideas?

```
Functions affected:
 Level 0: q
 Level 1: p1
 Level 2: p2
 Level 3: p3
 Level 2: p4
 Level 2: main
Functions not affected:
```

Example: transform functions with level >=3 to be not affected by rand()

```
bool runOnModule(Module &M) override {
  analyzeFunctions(M);

  bool modified = transformFunctions(M);

  analyzeFunctions(M);
  printStatus(M);

  return modified;
}
```

Previous inter-procedural analysis

Inter-procedural transformation

Example: transform functions with level >=3 to be not affected by rand()

```
bool transformFunctions (Module &M){
  bool modified = false;

  for (auto &F : M) {
    if (randomInfo[&F].r != invoked){
      continue ;
    }
    if (randomInfo[&F].level <= 2){
      continue ;
    }

    modified |= transformFunction(M, F);
  }

  return modified;
}
```

Example: transform functions with level >=3 to be not affected by rand()

```
bool transformFunction (Module &M, Function &F){
  bool modified = false;
  std::vector<Instruction *> toDelete;
  errs() << "START " << F.getName() << "\n";

  /* Reduce the impact to F.
   */
  for (auto &B : F) {
    for (auto &I : B) {
      if (auto call = dyn_cast<CallInst>(&I)){

        /* Fetch the callee.
         */
        auto *callee = call->getCalledFunction();
        if (callee == NULL){
          continue ;
        }

- 26 lines: Check the callee.-----------------------------
      }
    }
  }
```

Checking if

- the callee is rand()
  - Substitute call rand() with 1

- The callee invokes another function F2 at level – 1
  - Clone F2: F2’
  - Call F2’ instead of F2
  - Make F2’ not affected by rand

Example: transform functions with level >=3 to be not affected by rand()

```
/* Check the callee.
 */
if (callee->getName() == "rand"){
  errs() << "Changing invocations to \"rand\" from " << F.getName() << "\n";
  Value *constValue = ConstantInt::get(call->getType(), 1, true);
  call->replaceAllUsesWith(constValue);
  toDelete.push_back(call);
  modified = true;
  continue ;
}
if (randomInfo[callee].r != invoked) continue ;
if (randomInfo[callee].level >= randomInfo[&F].level) continue ;
```

Example: transform functions with level >=3 to be not affected by rand()

```
/* The callee needs to be cloned.
 */
errs() << "Cloning " << callee->getName() << " from " << F.getName() << "\n";
ValueToValueMapTy VMap;
auto clonedCallee = CloneFunction(callee, VMap);
call->replaceUsesOfWith(callee, clonedCallee);
randomInfo[clonedCallee] = randomInfo[callee];

/* Recursive check the callees of the cloned function.
 */
modified |= transformFunction(M, *clonedCallee);
```

Example: transform functions with level >=3 to be not affected by rand()

```
Functions affected:
 Level 0: q
 Level 1: p1
 Level 2: p2
 Level 3: p3
 Level 2: p4
 Level 2: main
Functions not affected:
```

```c
int q (void){
  return rand() % 10;
}
int p1 (void){
  return q();
}
int p2 (void){
  return p1();
}
int p3 (void){
  return p2();
}
int p4 (void){
  return p2() + p1();
}
int main (int argc, char *argv[]){
  int t = p3();
  int r = p1();
  printf("%d\n", t + r + p4());
  return 0;
}
```

```
Functions affected:
 Level 0: q
 Level 1: p1
 Level 2: p2
 Level 2: p4
 Level 2: main
Functions not affected:
 p3
 p2_cloned
 p1_cloned
 q_cloned
```

Another solution using function inlining

```
myF0(){
   …
   v = rand()
   …
}
```

```
myF1(){
   …
   myF0()
   …
}
```

```
myF2(){
   …
   myF1()
   …
}
```

```
myF3(){
   …
   myF2()
   …
}
```

```
myFx(){
   …
   myF0()
   …
}
```

```
myF0(){
   …
   v =
   …
}
```

```
myF3(){
   …
   v = 1
   …
}
```

```
myFx(){
   …
   myF0()
   …
}
```

Another solution using function inlining

```
bool runOnModule(Module &M) override {
  analyzeFunctions(M);

  bool modified = transformFunctions(M);

  analyzeFunctions(M);
  printStatus(M);

  return modified;
}
```

Previous inter-procedural analysis

Inter-procedural transformation

Another solution using function inlining

```
bool transformFunctions (Module &M){
  bool modified = false;

  for (auto &F : M) {
    if (randomInfo[&F].r != invoked){
      continue ;
    }
    if (randomInfo[&F].level <= 2){
      continue ;
    }

    modified |= transformFunction(M, F);
  }

  return modified;
}
```

```
bool transformFunction (Module &M, Function &F){
  std::vector<Instruction *> toDelete;
  errs() << "START " << F.getName() << "\n";

  /* Reduce the impact to F.
   */
  bool modified = false;
  bool inlined = false;
  for (auto &B : F) {
    for (auto &I : B) {
      if (auto call = dyn_cast<CallInst>(&I)){

        /* Fetch the callee.
         */
        auto *callee = call->getCalledFunction();
        if (callee == NULL){
          continue ;
        }
30 lines: Check the callee.-------------------------
  }

  /*
   * Delete instructions that are dead.
   */
  for (auto i : toDelete){
    i->eraseFromParent();
  }

 5 lines: Recursive inlining.------------------------

  errs() << "END " << F.getName() << "\n";
  return modified;
}
```

```
        /* Check the callee.
         */
        if (callee->getName() == "rand"){
          errs() << "Changing invocations to \"rand\" from " << F.getName() << "\n";
          Value *constValue = ConstantInt::get(call->getType(), 1, true);
          call->replaceAllUsesWith(constValue);
          toDelete.push_back(call);
          modified = true;
          continue ;
        }
        if (randomInfo[callee].r != invoked) continue ;
        if (randomInfo[callee].level >= randomInfo[&F].level) continue ;

        /* The callee needs to be cloned.
         */
        errs() << "Inlining " << callee->getName() << " to " << F.getName() << "\n";
        InlineFunctionInfo  IFI;
        inlined |= InlineFunction(call, IFI);
        if (inlined) {
          modified = true;
          break ;
        } else {
          errs() << "  Failed to inline\n";
        }
      }
    }
  }
```

```
if (inlined) {
  break ;
}
```

```
bool transformFunction (Module &M, Function &F){
  std::vector<Instruction *> toDelete;
  errs() << "START " << F.getName() << "\n";

  /* Reduce the impact to F.
   */
  bool modified = false;
  bool inlined = false;
  for (auto &B : F) {
    for (auto &I : B) {
      if (auto call = dyn_cast<CallInst>(&I)){

        /* Fetch the callee.
         */
        auto *callee = call->getCalledFunction();
        if (callee == NULL){
          continue ;
        }
30 lines: Check the callee.-----------------------
  }

  /*
   * Delete instructions that are dead.
   */
  for (auto i : toDelete){
    i->eraseFromParent();
  }
 5 lines: Recursive inlining.--------------------

  errs() << "END " << F.getName() << "\n";
  return modified;
}
```

```
/* Recursive inlining.
 */
if (inlined){
  transformFunction(M, F);
}
```

Today’s compilers

- Most old compilers avoid inter-procedural analysis
  - It’s expensive and complex
  - Not beneficial for most classical optimizations
  - Separate compilation + inter-procedural analysis requires recompilation analysis [Burke and Torczon’93]
  - Can’t analyze library code
- When are inter-procedural analyses useful?
  - Pointer analysis
  - Constant propagation
  - Object-oriented class analysis
  - Security and error checking
  - Program understanding and re-factoring
  - Code compaction
  - Parallelization
  - Vectorization

Modern uses of compilers

Other trends

- Cost of only having intra-procedural passes is growing
  - More functions than in the past and they’re smaller (OO languages)
  - Modern machines demand precise information (memory op aliasing)
- Cost of inlining is growing
  - Code bloat degrades efficacy of many modern structures
  - Procedures are being used more extensively
- Programs are becoming larger
- Cost of inter-procedural analysis is shrinking
  - Faster/more parallel machines
  - Better methods

Always have faith in your ability

Success will come your way eventually

Best of luck!