Inter-procedural CAT

Simone Campanoni
simonec@eecs.northwestern.edu
Procedures/functions

• Abstraction
  • Cornerstone of programming
  • Introduces barriers to analysis

• 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**

```c
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

![Diagram showing flow-sensitive analysis]

![Diagram showing flow-insensitive analysis]
Flow sensitivity example

Is $x$ constant?

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

Flow-sensitive analysis
- Computes 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
- 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?

if (x == 0)
    x = 4;           x = 5;
print(x)

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?

$$a = \text{id}(4); \quad b = \text{id}(5);$$

\[
\text{id}(x) \{ \text{return } x; \}\]

Context-sensitive analysis

- Computes 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

- 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 $\text{id}(4)$ 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

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

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

```plaintext
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/[0-3]
  • CallGraphWrappingPass
    • LLVM_callgraph/llvm/[4-6]
Generating a call graph with LLVM

```cpp
bool runOnFunction(Function &F) override {
  errs() << " Function \"" << F.getName() << "\"\n";
  for (auto &B : F) {
    for (auto &I : B) {
      if (auto call = dyn_cast<CallInst>(&I)){
        Function *callee = call->getCalledFunction();
        errs() << "  Callee " << callee->getName() << "\n";
        for (auto &B2 : *callee) {
          for (auto &I2 : B) {
            errs() << I2 << "\n";
          }
        }
      }
    }
  }
  return false;
}
```
DEMO
Using CallGraphWrappingPass

• Declaring your pass dependence

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

• Fetching the call graph

```cpp
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

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

• From node to callees

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

• From node to Function

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

① Sensitivity of analysis

② Single compilation

③ Separate compilations

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

⑤ Final remarks
Intra-procedural dataflow analysis

- How did we do previously?

```c
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-sensitive

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

```c
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;
}
```

- Accuracy?
- Performance?
  - No separate analysis
Inter-procedural dataflow analysis

Flow-sensitive

• How can we handle procedure calls?

  • Obvious idea: make one big CFG (control flow supergraph)

```c
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;
}
```

• Problem of invalid paths: dataflow facts from one call site “tainting” results at other call site
  • p analyzed with merge of dataflow facts from all call sites

• How to address this problem?

IN = {A}
IN = {A, G, H}
IN = {A, G, H, C}
IN = {A, G, H, C}
IN = {A, G, H}
IN = {A, G, H, C}
IN = {A, G, H, C}
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;
}

• Accuracy?
• Performance?
• 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)

• In LLVM:
  • You don’t need to implement this transformation, it already exists 😊
  • InlineResult InlineFunction(CallBase *, InlineFunctionInfo &, ... )

```c
InlineFunctionInfo IFI;
if (InlineFunction(call, IFI)) {
    Extra parameters are optional
    #include "llvm/Transforms/Utils/Cloning.h"
    ...
} else { ... }
```

Extra parameters are optional
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(...)  
  ... // 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

Example of function inlining: *inline the callee of B*

```c
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 code transformation: function inlining

```plaintext
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;
}
```

Another example of function inlining: inline the callee of D
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;
  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?
  \[ p(int \ n) \{ \ldots \ p(n-1); \ldots \} \]

• More generally, cycles in the call graph
Inter-procedural dataflow analysis
flow/context/path-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;
}

• Accuracy?
• Performance?
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: exponentially expensive
- Solution: separate compilation

```c
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;
}
```

IN = {A}
IN = {A, B:{G, H}}
IN = {A, C, B:{G, H}}
IN = {A, C, B:{G, H}, D:{G, H}}
Outline

① Sensitivity of analysis

② Single compilation

③ Separate compilations

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

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
  p
```

Accuracy? compared to
- Intra-procedural
- Inter-procedural flow/context-sensitive
- Inter-procedural flow/context/path-sensitive

```
IN = {A}
IN = {A, B}
IN = {A, B, C}
IN = {A, B, C, D}
```

```
main
  A
  B
  C
  D
  E
```

```
p
  F
  IN = {}
  G
  IN = {}
  H
  IN = {G, H}
  I
```

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: 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;
}

int p (int v) {
    F: if (v < 10)
    G:       m = 1;
    H: else
    I:       m = 2;
    J: return m;
}

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

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

```
main

IN = {A}

IN = {A, B}

IN = {A, B, C}

IN = {A, B, C, D}

p
```

Accuracy? compared to
- Intra-procedural
- Inter-procedural flow/context-sensitive
- Inter-procedural flow/context/path-sensitive

Summary: p returns Constant 1 if parameter is < 10
Constant 2 otherwise
Designing an inter-procedural analysis

Summary precision
e.g., constant/not-constant depending on the formal parameters
e.g., no summary (single compilation)

What to summarize
e.g., returning values
e.g., memory locations modified

Sensitivity
e.g., context
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
Context sensitivity

• Simplest solution: 1 copy per procedure

main

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

Summary: p doesn’t return a constant
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

IN = {A}

A

B

C

D

E

• 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;
    H:     else
    I:       m = 2;
    J: 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

• 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)

IN = \{A\}

IN = \{A, B\}

IN = \{A, B, C\}

main

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;
    H:       else
    I:       m = 2;
    J: 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;
}
```

Summary: p(7) returns 1
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;
}
```

Summary: 
- p(7) returns 1
- p(80) returns 2
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
main() {
    1: p();
    2: p();
}

p() {
    3: q();
}

q() {
    ...
}
main() {
  1: p();
  2: p();
}

p() {
  3: q();
}

q() {
  ...
}
Fibonacci: context insensitive

```c
main() {
  1: fib(7);
}

fib(int n) {
  if n <= 1
    x := 0
  else
    2: y := fib(n-1);
    3: z := fib(n-2);
    x:= y+z;
  return x;
}
```
Fibonacci: context sensitive, stack depth 1

```java
main() {
  1: fib(7);
}

fib(int n) {
  if n <= 1
    1: return
    1: call
  else
    2: y := fib(n-1);
    3: z := fib(n-2);
    x := y+z;
  return x;
}
```
main() {
  1: fib(7);
}

fib(int n) {
  if n <= 1
    x := 0
  else
    2: y := fib(n-1);
    3: z := fib(n-2);
    x:= y+z;
  return x;
}
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)
Other contexts

• More choices
  • Assumption sets
    What state (i.e., dataflow facts) hold at the call site?

• Combinations of contexts
  • e.g., Assumption set and object
Designing an inter-procedural analysis

Summary information
- e.g., constant/not-constant
- e.g., no summary (single compilation)

What to summarize

How to propagate

Sensitivity
- e.g., context
Outline

① Sensitivity of analysis

② Single compilation

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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?

• 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(7) returns 1
Summary: p(80) returns 2
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()`
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:
Example: identify functions that might get affected by rand()

Data structures:

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

std::map<Function *, random_info_t> randomInfo;
```
Example: identify functions that might get affected by rand()

```c
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()

```cpp
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()`

```c
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.
                }
            }
        }
    }
}

/* 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;
}
return ;
}
Example: identify functions that might get affected by `rand()`
Example: identify functions that might get affected by \texttt{rand()}

```c++
void identifyFunctionsIndirectlyAffected (Module \&M) {
    bool changed;
    do {
        changed = false;
        for (auto \&F : M) {
            if (randomInfo[\&F].r != invoked) {
                continue;
            }
        }
    } while (changed);
    return;
}
```

```c++
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()
Example: identify functions that might get affected by `rand()`
Computing inter-procedural summaries

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

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

h() {
  4:  h();
}

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;

• How can we identify indirect calls in LLVM?

Is l constant?
Indirect calls

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

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

Is l constant?
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 (){ void f (int p){ void f_2 (int p){ void f_2 (void){ void foo (){ f(7) int x = p + 3; int x = p + 3; int x = 10; 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 $\geq 3$ to be not affected by rand()
Example: transform functions with level $\geq 3$ to be not affected by rand()
Example: transform functions with level $\geq 3$ to be not affected by \texttt{rand()}

```cpp
bool runOnModule(Module &M) override {
    analyzeFunctions(M);
    bool modified = transformFunctions(M);
    analyzeFunctions(M);
    printStatus(M);
    return modified;
}
```
Example: transform functions with level $\geq 3$ to be not affected by `rand()`

```cpp
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 $\geq 3$ to be not affected by `rand()`

Checking if
- the callee is "rand()"
  - Substitute call `rand()` with "1"
- The callee invokes another function `F2` at level $-1$
  - Clone `F2`: `F2'`
  - Invoke `F2'` instead of `F2`
  - Make `F2'` not affected by `rand`
Example: transform functions with level $\geq 3$ to be not affected by rand()
Example: transform functions with level \( \geq 3 \) to be not affected by \texttt{rand()}

```c
/* 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 $\geq 3$ 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:
- p2 cloned
- p1 cloned
- q cloned

Does this inter-procedural transformation converge always?
Another solution using function inlining

```c
myF0()
{
    ...
    v = rand();
    ...
}
```

```c
myF1()
{
    ...
    myF0();
    ...
}
```

```c
myF2()
{
    ...
    myF1();
    ...
}
```

```c
myF3()
{
    ...
    myF2();
    ...
}
```

```c
myFx()
{
    ...
    myF0();
    ...
}
```

```c
myF0()
{
    ...
    v = 1;
    ...
}
```
Another solution using function inlining

```cpp
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

```cpp
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;
                }
                /* The callee needs to be cloned. */
                errs() << "Inlining " << callee->getName() << " to " << F.getName() << "\n";
                InlineFunctionInfo IFI;
                inlined |= InlineFunction(callee, IFI);
                if (inlined) {
                    modified = true;
                    break;
                } else {
                    errs() << " Failed to inline\n";
                }
            }
            i->eraseFromParent();
        }
    }
    errs() << "END " << F.getName() << "\n";
    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.
    
    /* Recursive inlining. */
    if (inlined) {
        transformFunction(M, F);
    }
    
    errs() << "END " << F.getName() << "\n";
    return modified;
}
Today’s compilers

• Most 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 of them 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