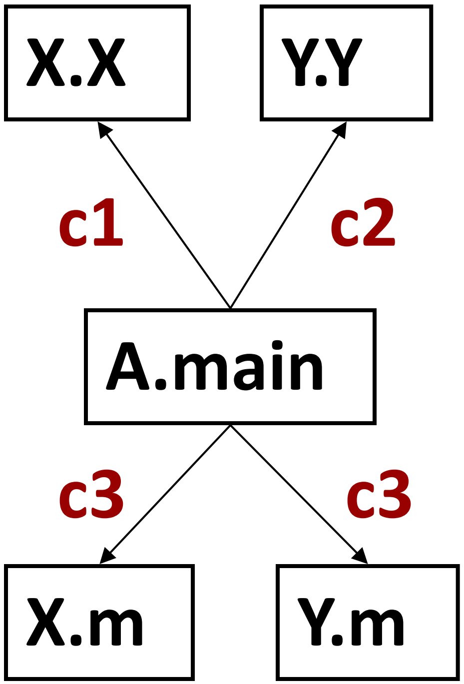
Construction of Call Graphs

- D. Grove and C. Chambers, “A framework for call graph construction algorithms,” ACM TOPLAS, vol. 23, no. 6, 2001
- Java overview slides on web page

Call Graphs

- Widely-used representation of calling relationships
  - Key component of interprocedural control-flow analysis
  - First step toward interprocedural dataflow analysis

```
class A {
  public static void main(…) {
    X x = new X(); // c1
    if (…) x = new Y(); // c2
    x.m(); // c3
  } }
class X { void m() {…} }
class Y extends X { void m() {…} }
```



Map of what is coming next

- Call graph construction for C
- Call graph construction for object-oriented languages (focus on Java)
  - Class Hierarchy Analysis
  - Rapid Type Analysis
- If you are not familiar with Java: brief overview of relevant Java features is available on the web page

Call Graph Construction for C

Problem: function pointers

Examples from "Precise Call Graphs for C Programs with Function Pointers", Ana Milanova, Atanas Rountev, and Barbara G. Ryder, *International Journal of Automated Software Engineering (JASE)*, 2004

```
typedef int (*PFB)();

struct parse_table {
    char *name;
    PFB func; };

int func1() { ... }
int func2() { ... }

struct parse_table table[] = {
    {"name1", &func1},
    {"name2", &func2} };

PFB find_p_func(char *s) {
1   for (i=0; i<num_func; i++)
2     if (strcmp(table[i].name,s)==0)
3       return table[i].func;
4   return NULL; }

int main(int argc,char *argv[]) {
    ...
5   PFB parse_func=find_p_func(argv[1]);
6   if (parse_func)
7     (*parse_func)();
8   else { ... } }
```

Another Example

```
struct _chunk { ... };
struct obstack {
    struct _chunk *chunk;
    struct _chunk *(*chunkfun) ();
    void (*freefun) (); };

void chunk_fun(struct obstack *h, void *f) {
    h->chunkfun = (struct _chunk *(*)()) f; }

void free_fun(struct obstack *h, void *f) {
    h->freefun = (void (*)()) f; }

int main() {
    struct obstack h;
    chunk_fun(&h,&xmalloc);
    free_fun(&h,&xfree); ... }
```

- What do we do with these function pointers?
- Simple answer: any function whose address is taken could possibly be called
  - Can try to restrict only to functions that “match” the types at the call site; be careful … .e.g., void *xmalloc(size_t)

Precise Resolution of Function Pointers

- Need interprocedural points-to analysis
  - Need a call graph! (flow of pointer values through parameter passing and procedure return values)
- Simple solution
  - Conservative call graph based on address-taken
  - Do points-to analysis
  - Re-compute the call graph using points-to information
- Or, call graph construction during points-to analysis
  - Start without any knowledge of f.p. calls
  - When a f.p. "shows up" in Pt(fp) at a call (*fp)(…), resolve it and update the points-to solution
  - Theoretically more precise; hard to design/implement

Call Graph Construction for C (cont'd)

- Problems come not only from function pointers …
- **Library calls**: typically, the pre-compiled libraries are not analyzed
  - Standard libraries
  - Third-party libraries
- A library call can trigger a callback to the program
  - E.g. in stdlib.h: void qsort(void *base, size_t nitems, size_t size, int (*compar)(const void *, const void*))
- **setjmp** and **longjmp**

  setjmp(jmp_buf env): stores the registers in env, including the stack pointer and the program counter

  longjmp(env): restores the registers; execution continues after the setjump program point

Methods Calls (Invocations in Java)

- **x.m(a,b):** method invocation at compile time
  - A target method is associated with the call
  - "compile-time target", "static target"
  - Based on the declared type of variable x

```
class A { void m(int p, int q) {...} ... }
class B extends A { void m(int r, int s) {...} ... }
A x;
x = new B();
x.m(1,2);
```

x has declared type A: compile-time target is A.m

javac encodes this in the bytecode (foo.class)

virtualinvoke x,<A: void m(int,int)>

Methods Calls (Invocations in Java)

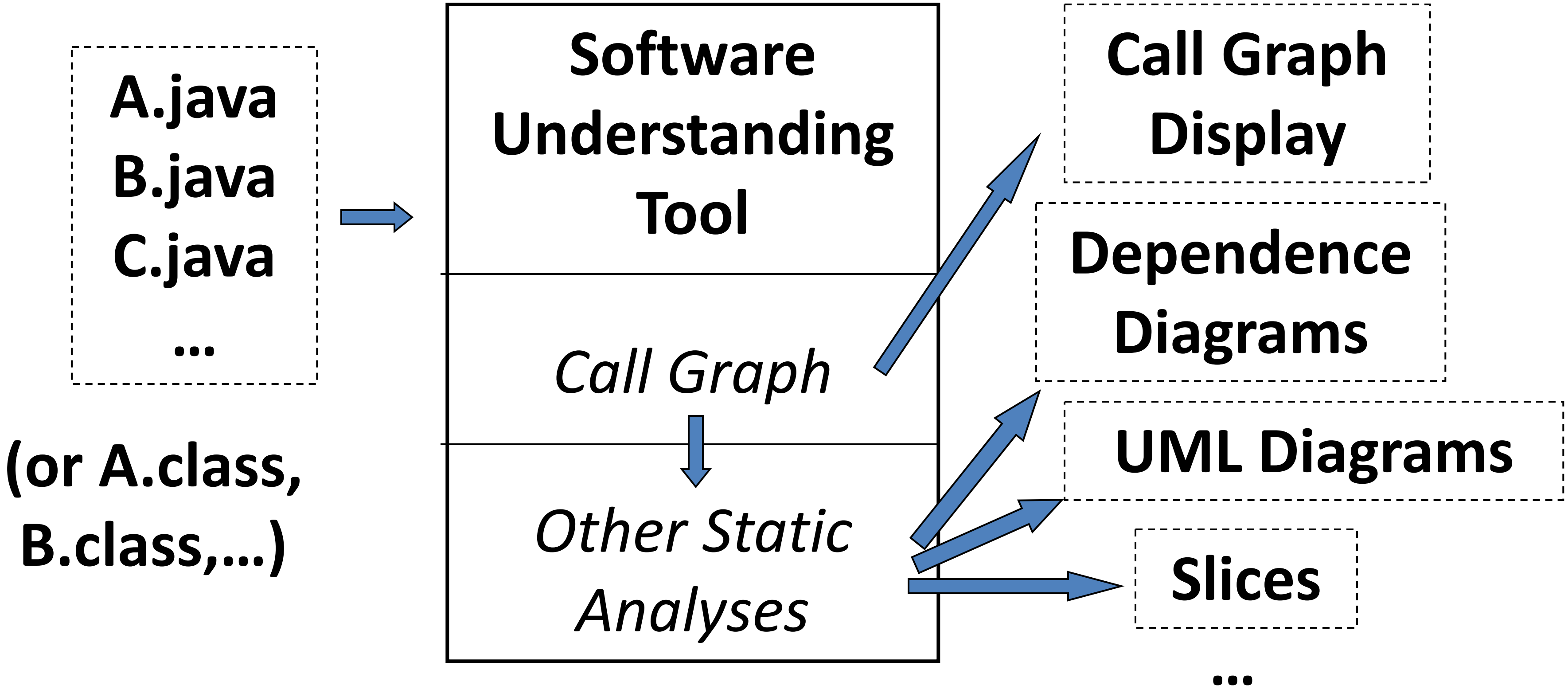
- **virtualinvoke x,<A: void m(int,int)>** inside the JVM
  - Look at the class Z of the object that x refers to at that particular moment
  - Search Z for a method with signature **m(int,int)** and return type **void**
  - If Z doesn't have it, go to Z's superclass, and so on upwards, until a match is found
  - Invoke the method on the object that is pointed-to by x

Run-time (dynamic) target: "lowest" method that matches the signature and the return type of the static target ("lowest" w.r.t. inheritance chain from Z to java.lang.Object)

This process is called virtual dispatch or method lookup

Call Graphs for Software Understanding

- Tools for software understanding
  - "smart" development environments (e.g., Eclipse), maintenance tools, visualization tools, etc.



Call Graphs for Optimizations

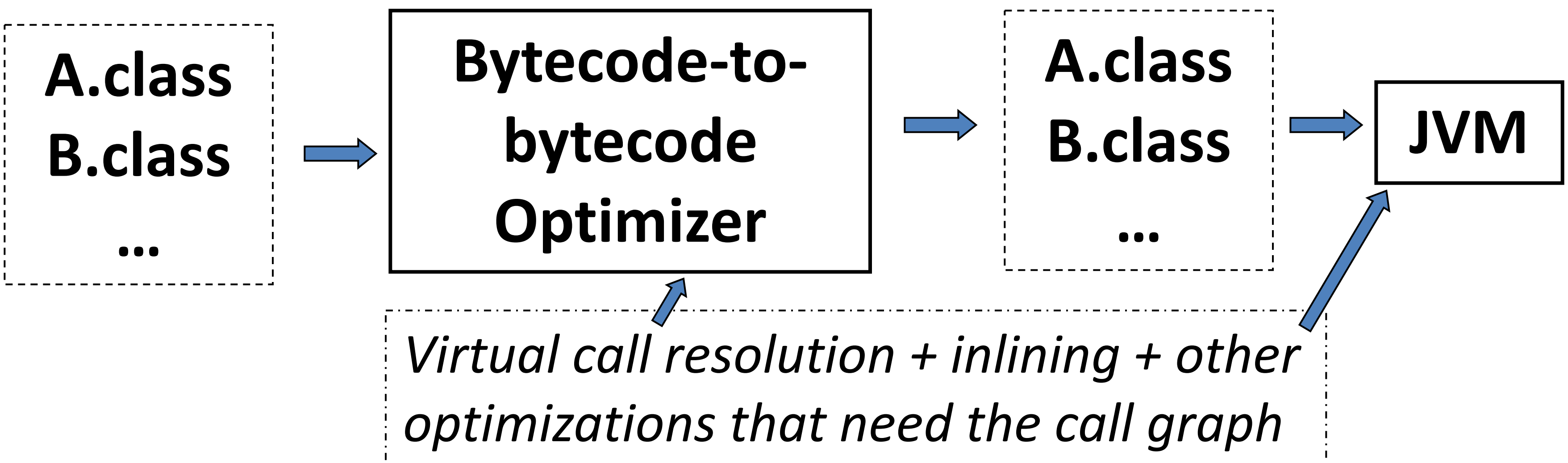
- Resolution of virtual calls
  - e.g. "virtualinvoke" in Java bytecode

```
class A { void m() { … } }
class B extends A { void m() { … } }
A a; . . . . a.m();
```

- If the call has only one outgoing edge in the call graph, the virtual dispatch at run time will always produce the same target
  - So, before the program is even executed, we can replace the virtual call with a "normal" call
  - Or, alternatively, after the program is loaded in the JVM, do run-time analysis and optimizations

Resolution of Virtual Calls

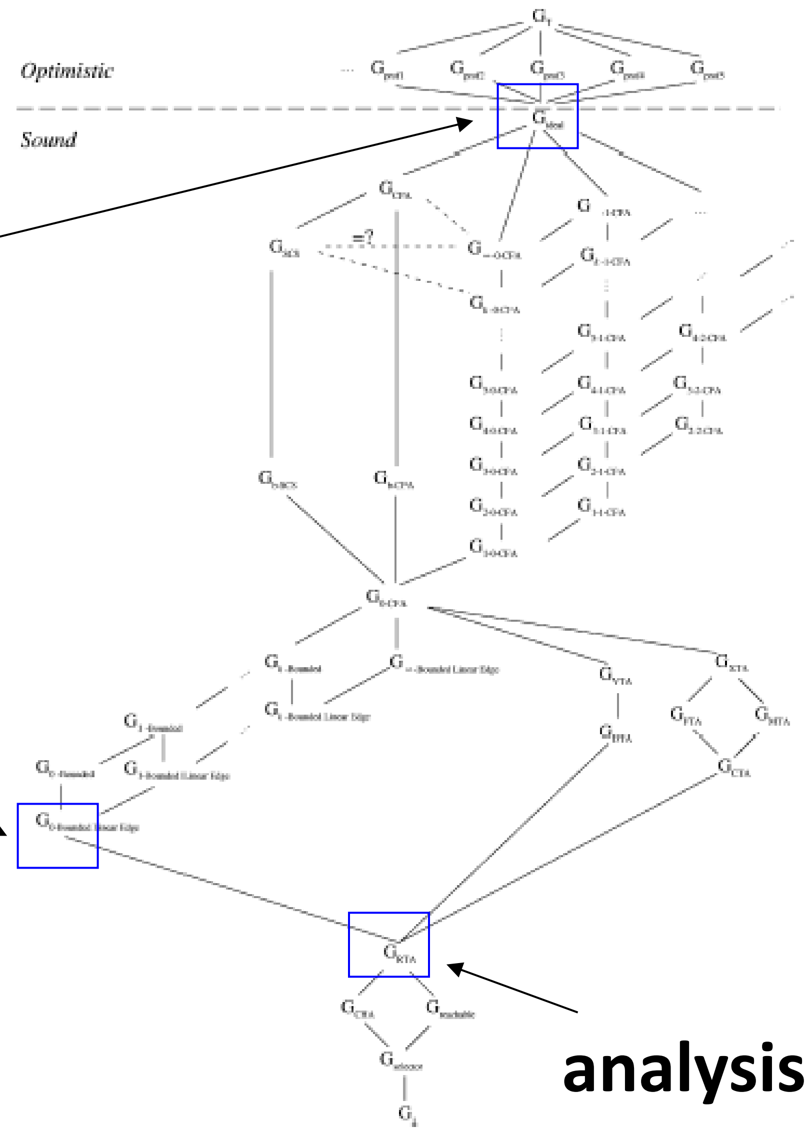
- Probably the oldest optimization problem for object-oriented languages
  - Smalltalk, C++, Java, many research languages
  - Goal 1: remove run-time virtual dispatch
  - Goal 2: inlining – insert the body of the called method in the caller (big performance win)



- Do this at compile time or at run time

The World of Call Graph Construction [Grove & Chambers 2001]

the perfect call graph: cannot be computed



analysis Y

analysis X

decreasing precision

X is less precise than Y: G_X is a superset of G_Y

Class Hierarchy Analysis (CHA)

- The simplest method for call graph construction
  - At the bottom of the previous slide
- Start from main, and perform reachability
  - The only tricky part: virtual calls
- Helper function used in CHA: dispatch
  - Simulates the effects of the run-time virtual dispatch (a.k.a. method lookup)
- Note: even CHA gets tricky in the presence of dynamic class loading, reflection, native methods, etc.
  - "Assumption Hierarchy for a CHA Call Graph Construction Algorithm", Jason Sawin and Atanas Rountev, *IEEE Int. Working Conference on Source Code Analysis and Manipulation, 2011*

dispatch

```
dispatch(call_site s, receiver_class rc)
  sig = signature_of_static_target(s)
  ret = return_type_of_static_target(s)
  c = rc;
  while (c != null)
      if class c contains a method m with
      signature sig and return type ret
            return m
      c = superclass(c)
  print “ERROR: this should be unreachable”
```

One Possible Implementation of CHA

```
Queue worklist
CallGraph Graph
worklist.addAtTail(main);
Graph.addNode(main)
while (worklist.notEmpty())
    m = worklist.getFromHead();
    process_method_body(m);
```

process_method_body(method m)

```
for each call site s inside m
  if s is a static call or a constructor call or
  a call through super
      add_edge(s)
  if s is a virtual call v.n(…)
      rcv_class = type_of(v);
      for each non-abstract class c that is a
      subclass of rcv_class or rcv_class itself
          x = dispatch(s,c)
          add_edge(s,x)
```

add_edge

add_edge(call_site s)

```
// for static calls, constructor calls, and calls through super
m = target(s);
if m is not in Graph
        Graph.addNode(m);
        worklist.addAtTail(m);
Graph.addEdge(s,m)
```

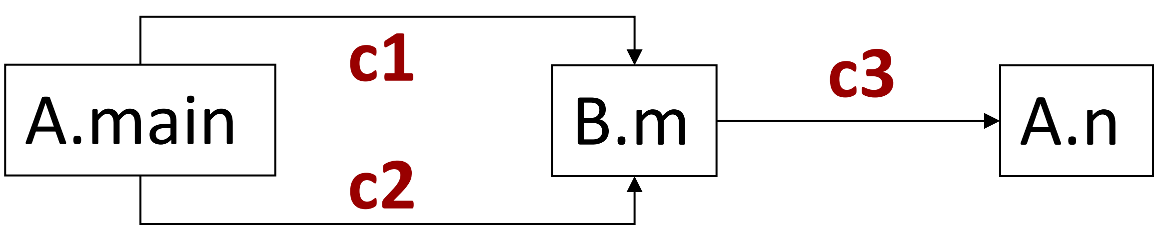
add_edge(call_site s, run_time_target x)

```
// same here
```

Example

```
class A {
  void m() { }
  void n() { }
  static void main(...) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }
```

```
class B extends A {
  void m() {
        A x = new A();
        x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```



the "real" call graph

Example

```
class A {
  void m() { }
  void n() { }
  static void main(...) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }
```

```
class B extends A {
  void m() {
        A x = new A();
        x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```

workist: add and then remove A.main

c1: dispatch for rcv_type B -> target B.m

c1: dispatch for rcv_type C -> target C.m

Example

- State after processing c1
  - worklist = {B.m,C.m}
  - Graph.Nodes = {A.main, B.m, C.m}
  - Graph.Edges = { (c1,B.m), (c1,C.m) }
- Edge (c1,C.m) is spurious (infeasible)
  - There is no execution of the program in which c1 invokes C.m
- More precise analyses produce fewer spurious edges
  - Typically are more expensive (time/memory)

Example

```
class A {
  void m() { }
  void n() { }
  static void main(...) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }

class B extends A {
  void m() {
        A x = new A();
        x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```

c2: call through **a**, which is of type A

c2: dispatch for rcv_type A -> target A.m

c2: dispatch for rcv_type B -> target B.m

c2: dispatch for rcv_type C -> target C.m

Example

- State after processing c2
  - worklist = {B.m,C.m,A.m}
  - Graph.Nodes = {A.main, B.m, C.m, A.m}
  - Graph.Edges = {(c1,B.m),(c1,C.m), (c2,A.m),(c2,B.m),(c2,C.m) }
- Edges (c2,A.m) and (c2,C.m) are spurious
- After we are done with A.main, take the next method at the head of the queue
  - in this case B.m

Example

```
class A {
  void m() { }
  void n() { }
  static void main(...) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }

class B extends A {
  void m() {
      A x = new A();
      x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```

c3: call through **x**, which is of type A

c3: dispatch for rcv_type A -> target A.n

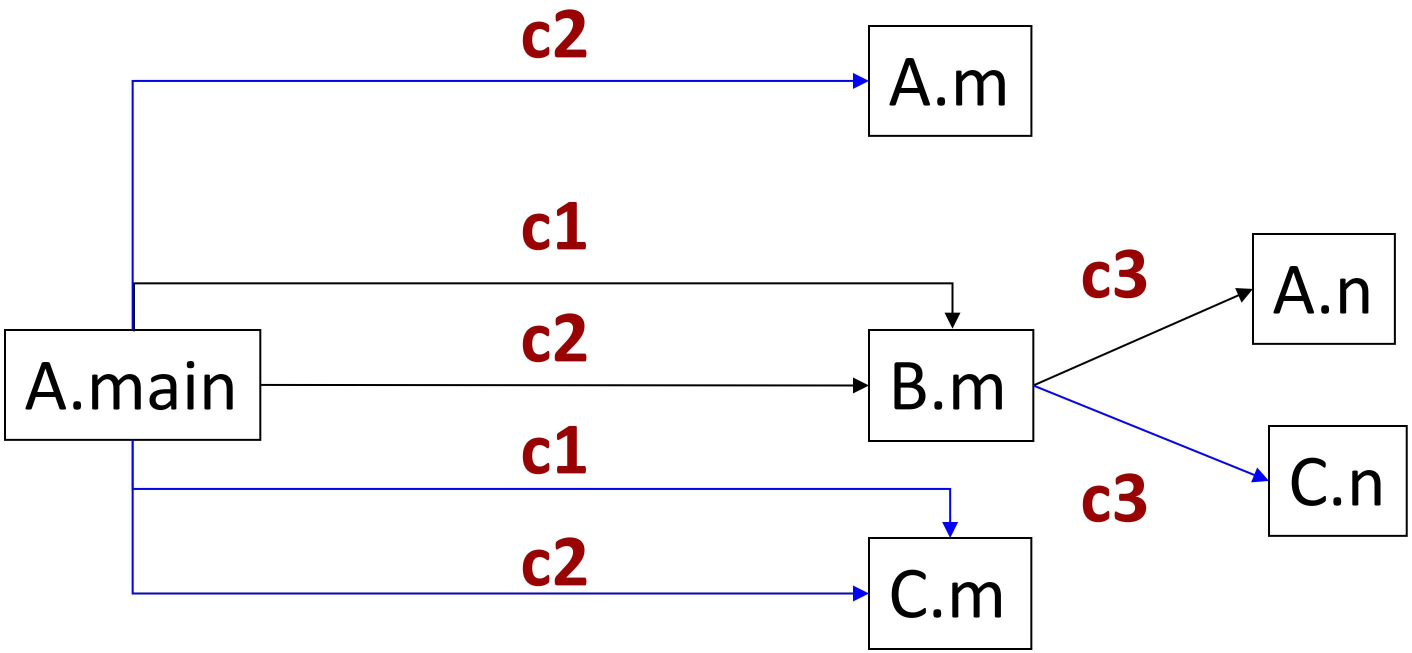
c3: dispatch for rcv_type B -> target A.n

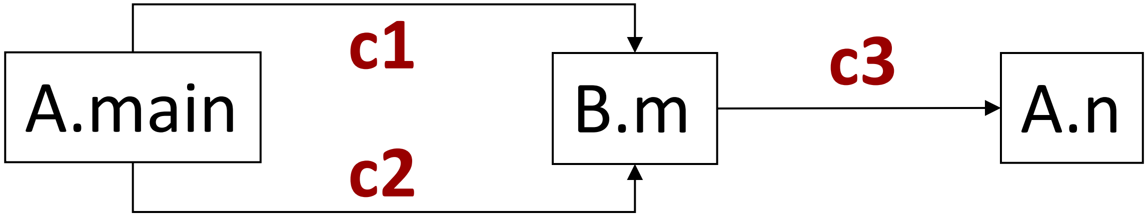
c3: dispatch for rcv_type C -> target C.n

Example

- State after processing c3
  - worklist = {C.m,A.m,A.n,C.n}
  - Graph.Nodes = {A.main, B.m, C.m, A.m, C.n}
  - Graph.Edges = {(c1,B.m), (c1,C.m), (c2,A.m), (c2,B.m), (c2,C.m), (c3,A.n), (c3,C.n) }
- Edge (c3,C.n) is spurious
- The rest of the methods in the queue have empty bodies, so the rest of the algorithm doesn’t create any new edges/nodes

Resulting Call Graph





the “real” call graph

Rapid Type Analysis

- An analysis that is the next step after CHA
  - Guaranteed to produce a call graph that is a subset of the call graph produced by CHA
  - Still quite imprecise. There are many analyses that are better than RTA
- “type analysis”
  - Idea: given a reference/pointer variable, try to figure out what types of objects this variable may refer/point to

Rapid Type Analysis

- Basic insight: some classes are never instantiated in reachable methods
  - i.e. there is never a new X() expression
- Main reason: programs that are built on top of libraries
  - Large parts of the library code are unused
- When we try to figure out the possible run-time targets of a virtual call, we can safely ignore classes that are not instantiated

One Possible Implementation of RTA

```
Queue worklist
CallGraph Graph
worklist.addAtTail(main);
Set instantiated_classes
Map pending_call_sites
Graph.addNode(main)
while (worklist.notEmpty())
    m = worklist.getFromHead();
    process_method_body(m);
```

process_method_body(method m)

```
for each expression new X inside m
    if (X ∉ instantiated_classes)
        add X to instantiated_classes
        resolve_pending(X)
for each call site s inside m
    if s is a static call or a constructor call or
    a call through super
        add_edge(s)
  if s is a virtual call v.n(...)
        rcv_class = type_of(v);
        for each non-abstract class c that is a
        subclass of rcv_class or rcv_class itself
            process_rcv_class(c,s)
```

process_rcv_class

```
process_rcv_class(class c, call_site s)
  x = dispatch(s,c)
  if c ∈ instantiated_classes
     add_edge(s,x)
  else // c is not currently instantiated,
       // but in the future it may be, so
       // we have to remember this edge
     remember (s,x) in pending(c)
```

resolve_pending(class c)

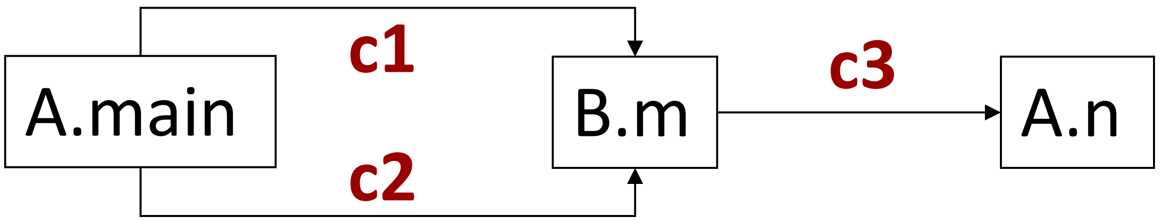
```
// class c became instantiated, and
// we need to add all pending edges
for each (s,x) in pending(c)
    add_edge(s,x)
```

Called by process_method_body :
for each expression **new X**
  if (**X** ∉ instantiated_classes)
    add **X** to instantiated_classes
      resolve_pending(X)

Example

```
class A {
  void m() { }
  void n() { }
  static void main(...) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }
```

```
class B extends A {
  void m() {
      A x = new A();
      x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```



the “real” call graph

Example

```
class A {
  void m() { }
  void n() { }
  static void main(…) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }

class B extends A {
  void m() {
        A x = new A();
        x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```

worklist: add and then remove A.main

instantiated_classes = {B}

c1: dispatch for rcv_type B -> target B.m

c1: dispatch for rcv_type C -> target C.m

Example

- process_rcv_class(c1,B)
  - Since B is instantiated, add edge (c1,B.m)
- process_rcv_class(c1,C)
  - Since C is not instantiated, we do not add edge (c1,C.m) to the call graph
    - Remember (c1,C.m) in pending(C)
- State after processing c1
  - worklist = {B.m}
  - Graph.Nodes = {A.main, B.m}
  - Graph.Edges = { (c1,B.m)}

Example

```
class A {
  void m() { }
  void n() { }
  static void main(…) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }
```

```
class B extends A {
  void m() {
    A x = new A();
    x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```

c2: call through **a**, which is of type A

c2: dispatch for rcv_type A -> target A.m

c2: dispatch for rcv_type B -> target B.m

c2: dispatch for rcv_type C -> target C.m

Example

- (c2,A): add (c2,A.m) to pending(A)
- (c2,B): add (c2,B.m) to Graph
- (c2,C): add (c2,C.m) to pending(C)
- State after processing c2
  - worklist = {B.m}
  - Graph.Nodes = {A.main, B.m}
  - Graph.Edges = {(c1,B.m), (c2,B.m)}
  - pending(A) = {(c2,A.m)}
  - pending(C) = {(c1,C.m),(c2,C.m)}

Example

```
class A {
  void m() { }
  void n() { }
  static void main(...) {
    B b = new B();
    b.m(); // c1
    A a = b;
    a.m(); // c2 } }

class B extends A {
  void m() {
        A x = new A();
        x.n(); // c3 } }
class C extends B {
  void m() { }
  void n() { } }
```

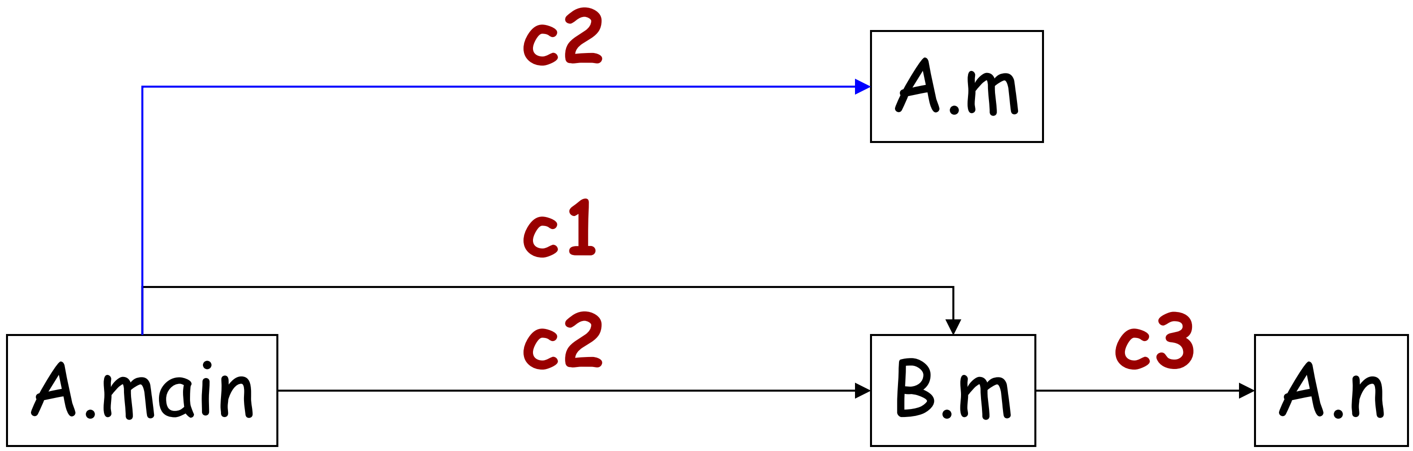
instantiated_classes = {B,A}

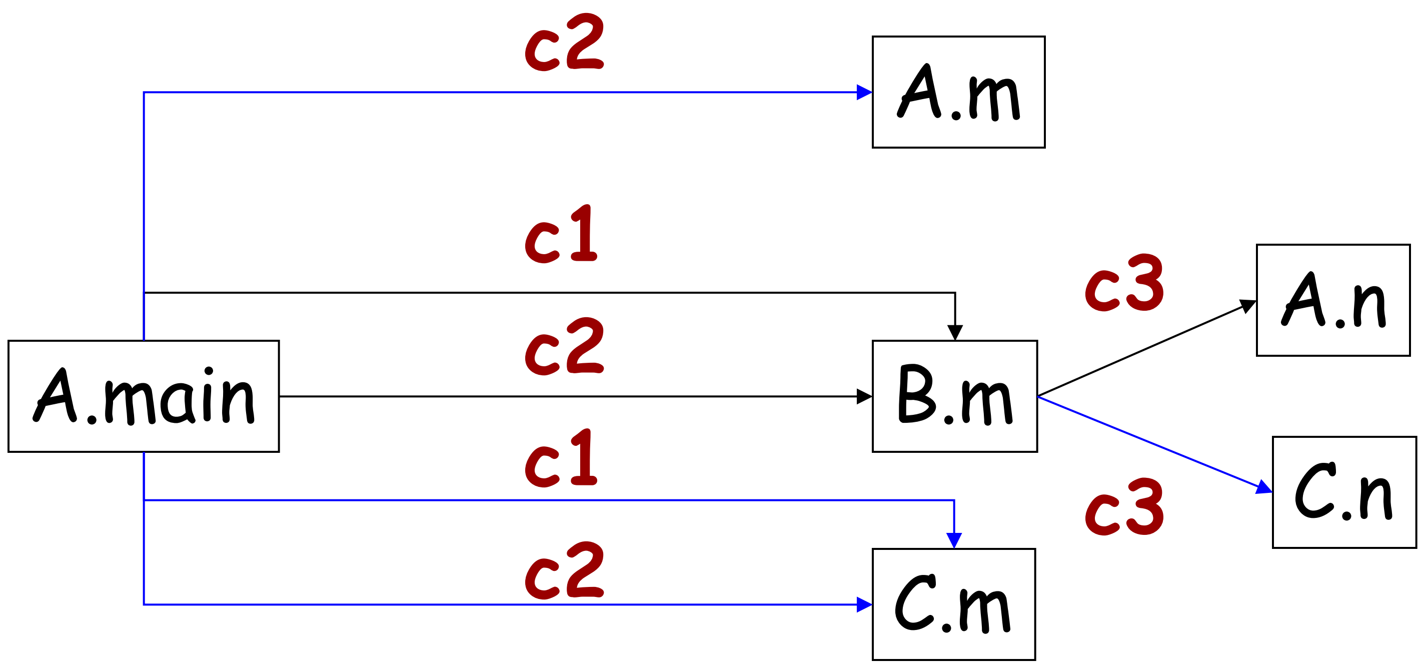
triggers a call to resolve_pending(A), with pending(A) = { (c2,A.m) }

Example

- resolve_pending(A)
  - Graph.Nodes = {A.main, B.m, A.m}
  - Graph.Edges = {(c1,B.m), (c2,B.m), (c2,A.m)}
  - worklist = {A.m}
- At call site c3: x.n()
  - x is of type A => A, B, or C possible
  - A and B are instantiated, there is no B.n; so, edge (c3,A.n) is added to the graph
- A.m and A.n have empty bodies, and the graph is completed

RTA vs. CHA

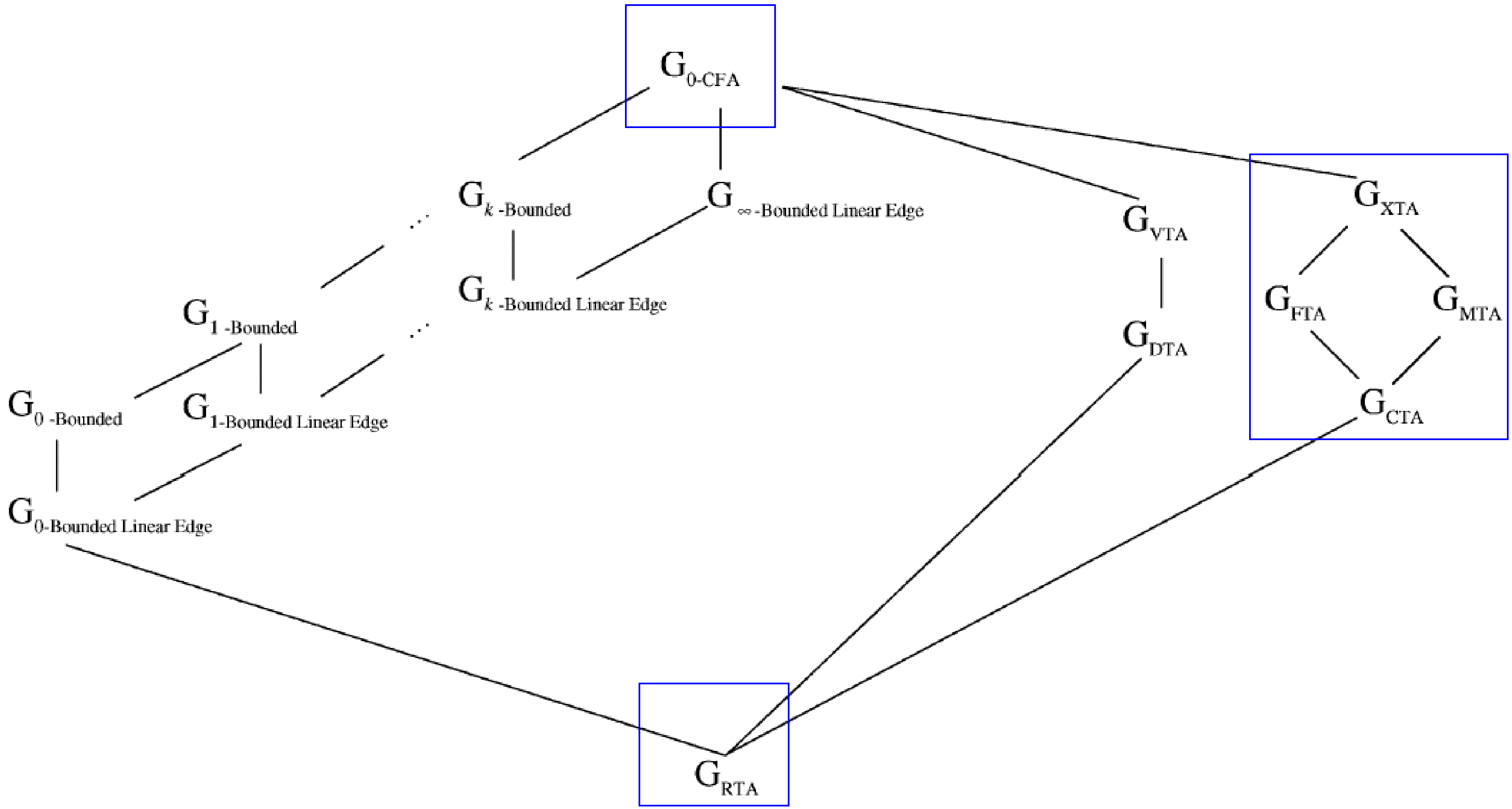




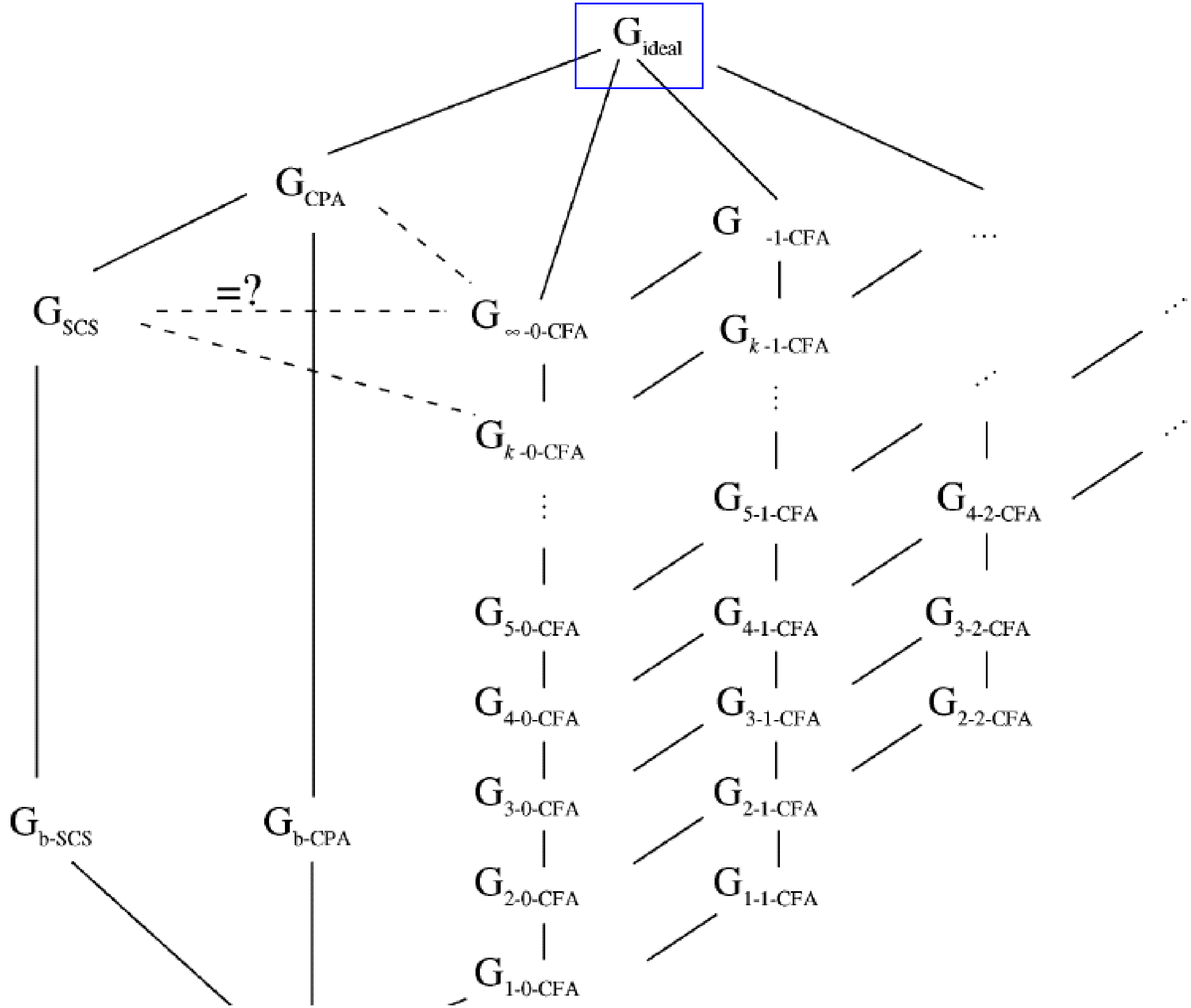
RTA vs. CHA

- The key advantage: RTA was able to determine that C is never instantiated in reachable methods
  - This means that C.m and C.n can never be targets
- Of course, this is just one possible source of imprecision
  - Analyses that are "more aggressive" than RTA focus on some of these sources

Some Existing Analyses



More Existing Analyses



Class Analysis

- **Class analysis**: given a reference variable **x**, what are the classes of the objects that **x** may refer to?
  - a.k.a. "type analysis" (e.g., RTA)
  - After a class analysis, it is trivial to construct the call graph
    - As a separate post-processing phase
- Most class analyses construct the call graph on the fly during the analysis
  - For object-oriented languages, "call graph construction", "class analysis", and "type analysis" are often used as synonyms
- Points-to analysis can be thought of as a particular form of class/type analysis
  - Next: "classic" points-to analysis, closely related to 0-CFA type analysis (see two slides earlier)