Dynamically checking type-correctness of whole programs

(work newly in-progress).

Stephen Kell

stephen.kell@cl.cam.ac.uk

Computer Laboratory
University of Cambridge

Wanted (naive version): check this!

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker, (struct commit *)obj))
    return -1;
  return 0;
}
```

Wanted (naive version): check this!

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker, (struct commit *)obj))
    return -1;                                 ↖   ↗
  return 0;                                  CHECK this
}                                           (at run time)
```

Wanted (naive version): check this!

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker, (struct commit *)obj))
    return -1;                              ↖   ↗
  return 0;                               CHECK this
}                                        (at run time)
```

But also wanted:

- binary compatible
- source compatible
- reasonable performance
- avoid being C-specific!*

* mostly…

This talk in one slide

I will describe libcrunch, which is

- an infrastructure for run-time type checking
- encodes type checks as assertions
- no guarantee of “safety” (but. . .)
- support idiomatic unsafe code
- checks inserted by per-language front-ends
- no binary interface changes
- no *source* changes, usually*

(* but sometimes out-of-band guidance helps)

Introducing libcrunch

The user's view:

```
$ crunchcc -o myprog ...     # + other front-ends
$ ./myprog                        # runs normally
$ LD_PRELOAD=libcrunch.so ./myprog # does checks
```

where

- myprog contains *type assertions* (we'll see how)
- normally "disabled"
- enabled when libcrunch is linked in
- compiler [wrapper] inserts assertions automatically

What is run-time type checking?

Check every program operation is “type-correct”, i.e.

- program state is a collection of stored values
- … allocated as instances of some “data type”
- data types signify meaning
- operations consume and produce stored values…

More precise definition wanted…

- for C, plan to use Cerberus to create formal definition

What checks are we interested in?

Recall the example:

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker, (struct commit *)obj))
    return -1;
  return 0;
}
```

Primitive errors are not our concern

- even C compilers check primitive type-correctness

First-order and up

- all about pointers
- first cut: check casts (& implicit strengthenings) in C

How it works, in a nutshell

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker,

              (struct commit *)obj))
    return -1;
  return 0;
}
```

How it works, in a nutshell

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker,
       (assert(__is_a(obj, "struct commit")), // or something like this
           (struct commit *)obj)))
    return -1;
  return 0;
}
```

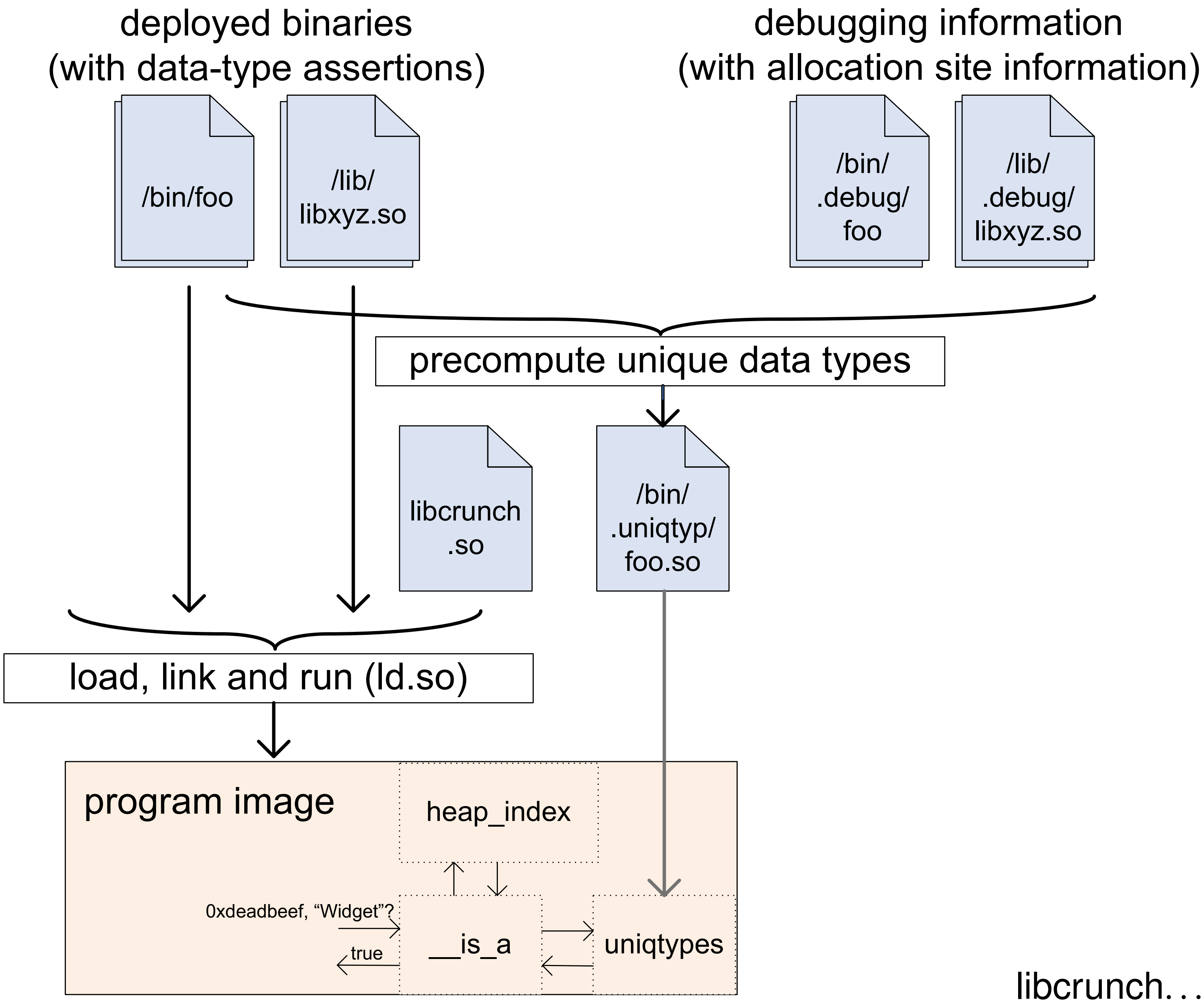
How it works, in a nutshell

```
if (obj->type == OBJ_COMMIT) {
  if (process_commit(walker,
       (assert( __is_a (obj, "struct␣commit")), // or something like this
           (struct commit *)obj)))
    return -1;
  return 0;
}
```

To make this work, we need:

- type information on every *allocation* in program
- efficient run-time representation of types
- fast __is_a function
- something to write these assertions for us

Idealised view of libcrunch operation



Type info for each allocation

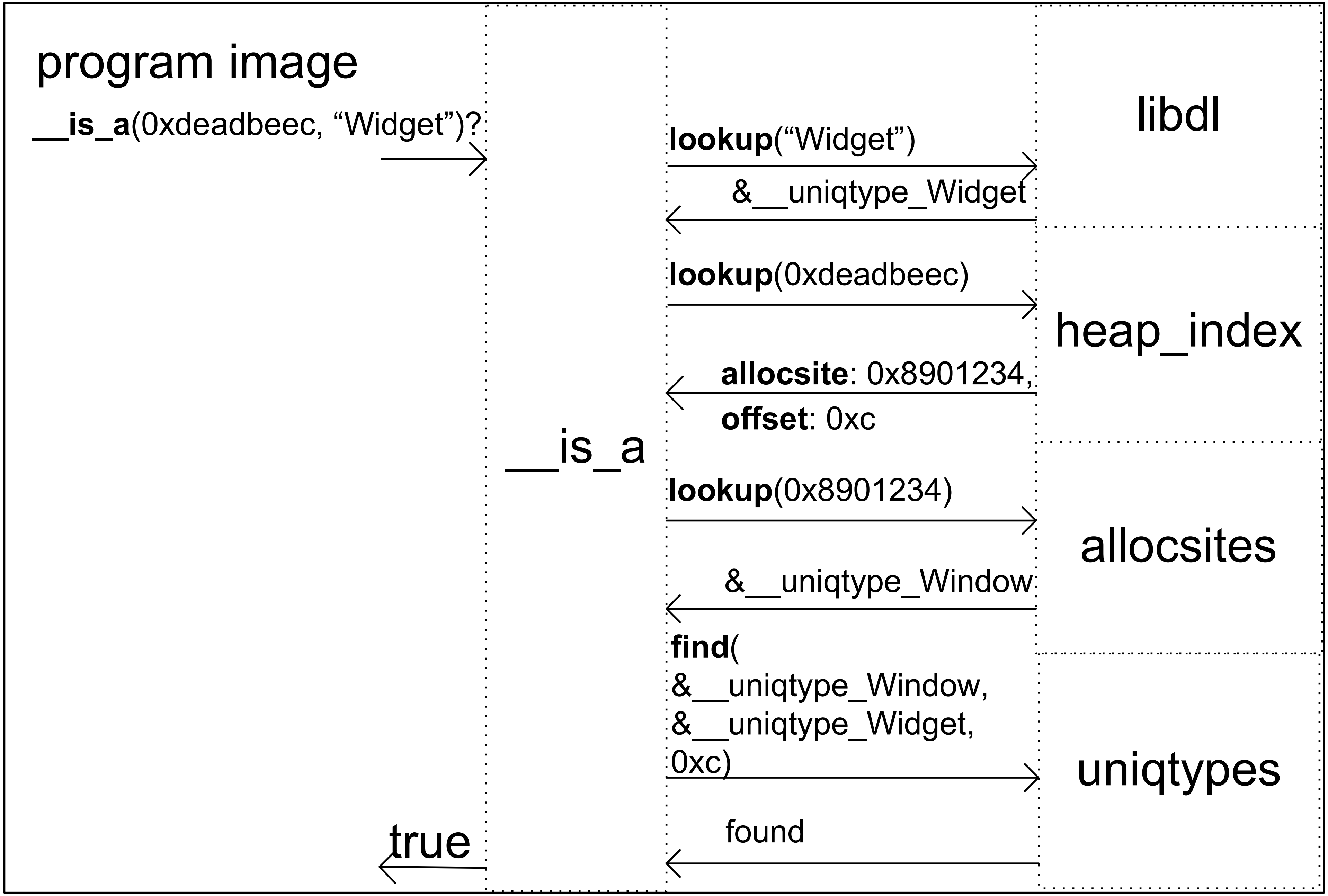
Type info for allocation is reasonable because

- … to allocate, you need a size
- three kinds of allocations: static, stack, heap
- assume all heap allocators are instrumented…

Assume we have debug info

- handles stack and static cases

What happens at run time?



Looking up object metadata (1)

Recall: need info about an arbitrary object's *allocation*

- … given an arbitrary pointer

Stack case

- walk the stack + use debug info for locals/args

Static case

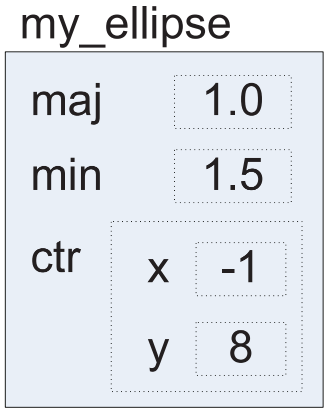
- use debug info

Heap case

- hard! might be an *interior* pointer
- use clever virtual memory-based data structure (ask me)

__is_a, containment…

A pointer might satisfy __is_a $>$ 1 way



```
struct ellipse {
  double maj;
  double min;
  struct point {
    double x, y;
  } ctr;
}
```

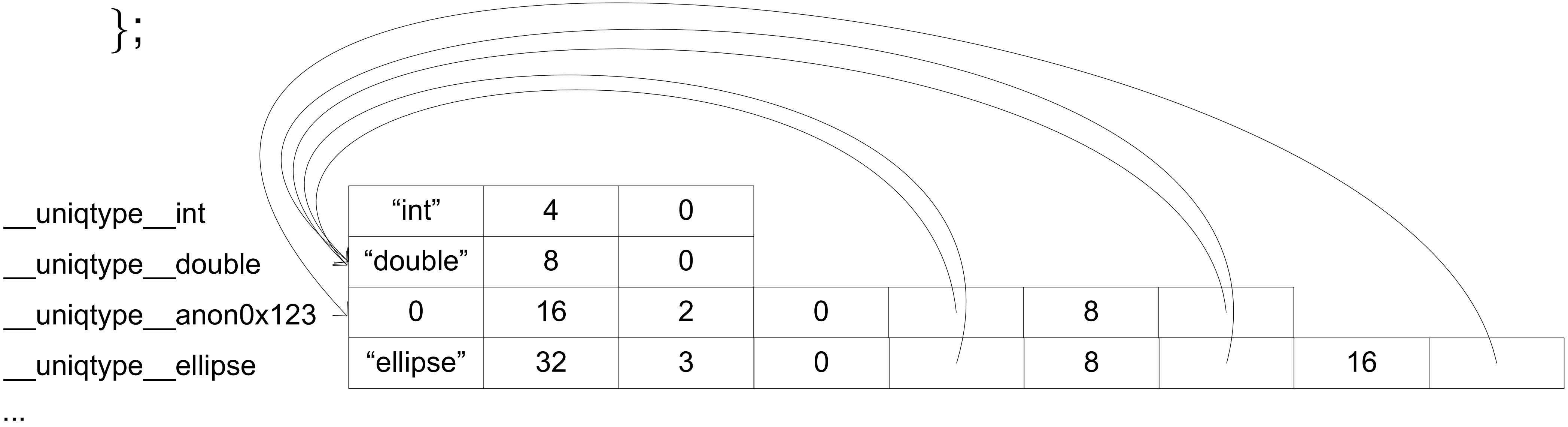
Consider “what is”

- &my_ellipse
- &my_ellipse.ctr
- …

(Subclassing is usually implemented this way.)

Efficiently reifying data types at run time

```
struct ellipse {
    double maj, min;
    struct { double x, y; } ctr ;
};
```



__uniqtype__int	“int”	4	0						
__uniqtype__double	“double”	8	0						
__uniqtype__anon0x123	0	16	2	0		8			
__uniqtype__ellipse	“ellipse”	32	3	0		8		16	

...

Reify data types *uniquely*, describing *containment*

- uniqueness → “exact type” test is a pointer comparison
- __is_a() is a simple, fast search through this structure

Other flavours of check

__is_a is a nominal check, but we can also write

- __like_a – “1-structural” (unwrap one level)
- __phys_a – “*-structural” (unwrap maximally)
- __refines – may instantiate padding (à la sockaddr)
- __named_a – opaque workaround

Notes about memory correctness

We (currently) do nothing about memory correctness! E.g.

```
void f () {
  int a;
  int bs[2];
  for (int *p = &bs[0]; p <= 2; ++p) { /* ... */ }
}
```

- bug-finding, not verification, not security…
- faster! avoid per-pointer (cf. per-object) metadata
- most memory-incorrect programs are type-incorrect…
- could "force a cast" after pointer arithmetic

SoftBound + CETS do a pretty good job

- we *could* replicate them…

Recap

What we've just seen is

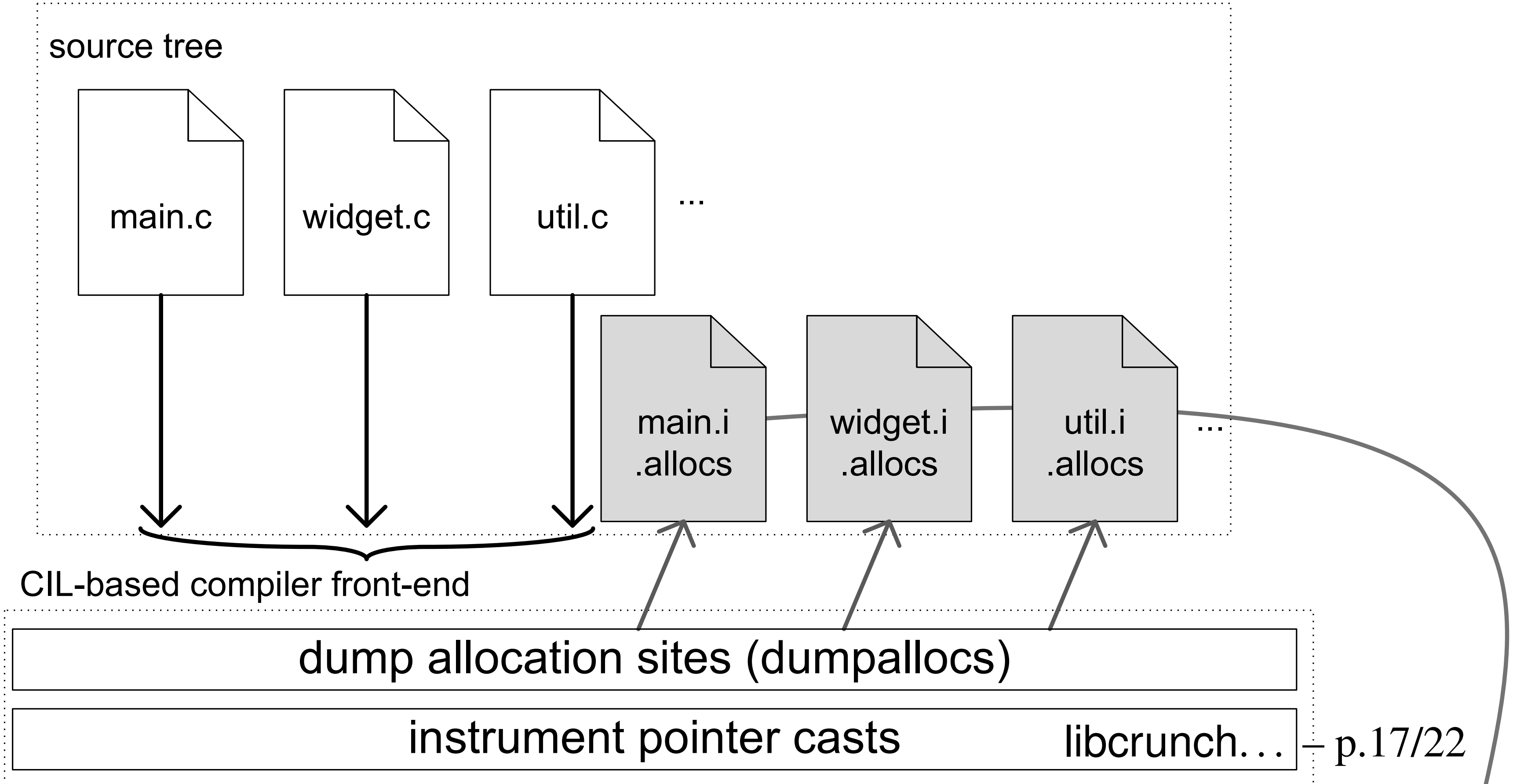
- a runtime system for evaluating type assertions
- fast (biggest slowdown seen 20%; often <10%)
- (by design) flexible
- a "whole program" language-neutral design
- binary compatible

What about *source* compatibility?

libcrunch prototype: C front-end

Who inserts the assertions?

- instrumentation: “one assertion per pointer cast”
- analysis: “what data type is being malloc()’d?”
- … guess from use of sizeof



source tree

main.c

widget.c

util.c

...

main.i .allocs

widget.i .allocs

util.i .allocs

...

CIL-based compiler front-end

dump allocation sites (dumpallocs)

instrument pointer casts

Complications (1)

With metadata

- dynamic loading (merge uniqtypes)
- non-standard alloc functions (explicit support)

With compilers (currently false pos/negs)

- address-taken temporaries (fix compiler for debug info)
- varargs actuals
- alloca()

+ assert() usually isn't quite what you want…

Complications (2)

With the C front end (false pos or "intervention required")

- very weird uses of sizeof
- weird avoidance of sizeof
- char special case
- object re-use
- unions (but mostly doable! three cases; ask me)
- some cases of multiple indirection cause false pos

Brutal honesty moment: a real false positive

```
void sort_eight_special (void **pt){
void *tt [8];
register int i ;
    for(i=0;i<8;i++)tt[i]=pt[i];
    for(i=XUP;i<=TUP;i++){pt[i]=tt[2*i]; pt[OPP_DIR(i)]=tt[2*i+1];}
}
```

Client then does (making libcrunch print a warning)

```
neighbor = (int **)calloc(NDIRS, sizeof(int *));
/* ... */
 sort_eight_special ((void **) neighbor );
```

Question: is this valid C?

What’s in it for REMS

Check “agreement” between libcrunch and cerberus

- inclusion, for the relevant subset of complaints

Tool for exploring behaviour of real programs

- good at turning up “dodgy” code (oft also “correct”!)

Representative of a wider set of tools…

- insight for bridging between source and run-time worlds
- linking tie-in…

Recap, conclusions

We've seen

- a runtime infrastructure for fast checking
- a prototype C front-end

Remaining challenges for the run-time part:

- finish the paper…
- multi-language story
- support more complex specifications ("types")

Code is here: https://github.com/stephenrkell/

Thanks for listening. Questions?