Run-time type checking of whole programs

and other stories

Stephen Kell

stephen.kell@usi.ch

University of Lugano

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!

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if (obj->type == OBJ_COMMIT) {
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}
```

CHECK this

(at run time)

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    if (process_commit(walker, (struct commit *)obj))
        return -1;
    return 0;
}
```

CHECK this

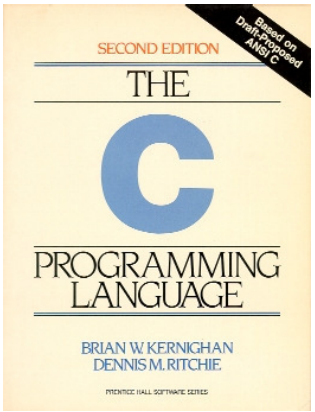
(at run time)

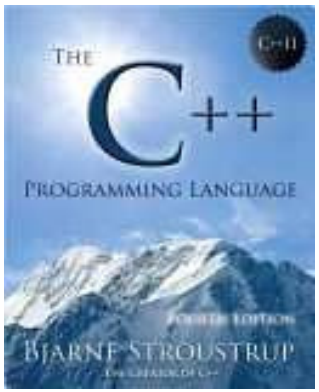
But also wanted:

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

* mostly...

Wanted (truthful version)





. . .

- understand "type-correct" compositions of these
- static checking too!
- other "type systems" (a.k.a. classes of specification) too
- too much to talk about today. . .

This talk in one slide

I 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)

Why unsafe languages?

- fine control of resource utilisation
- talk directly to operating system
- talk directly to hardware
- freedom to simulate new language-level abstractions
- freedom to violate program-level abstractions
- manual optimisation
- re-use existing code

State of the art: a straw man

Competitive existing approaches are broadly alike:

- conflate type- with memory-correctness
- demand proof
- reject many correct programs
- break library compatibility
- specific to C
- and/or high run-time overhead

CCured, Deputy, Chandra & Reps ’99, Condit et al ’09,. . .

Terminology (a minefield)

"type"

- for this talk: a data type (named set of values)
- normally I'm with Pierce, but life's too short

"safety"

- once upon a time, meant a run-time property
- now has vague meaning

"soundness"

- opposing usages exist

I prefer "type correctness", "verified type correctness"

Introducing libcrunch

The vision:

- `$ ./myprog # runs normally`
- `$ LD_PRELOAD=libcrunch.so ./myprog # does checks`

where

- myprog contains *type assertions*
- normally "disabled"
- enabled when libcrunch is linked in
- compiler [wrapper] inserts assertions automatically

What is run-time type checking?

Ideally, checks every program operation is "type-correct"

- respects the *meaning* of its *run-time* input values
- as ascribed by programmers using *data types*
- all storage is *allocated* with a data type

Examples

```
int a;  char b;  double f(int, char*);
f(a, &b);                    // okay!
f(b, &a);                    // not okay
b = f(a, &b);                // okay ( implicit  conversion inserted)
void *p = get_object();  void *q = (void *) 0xdeadbeef;
f(*(int*)p, (char*)q);  // depends...
```

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;
}
```

For us, the interesting values are pointers

- even C checks primitive type-correctness
- $\rightarrow$ limited BCPL support :-(
- C requires casts on "dangerous" pointer ops

Subtle question: what *invariant* do we want to maintain?

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

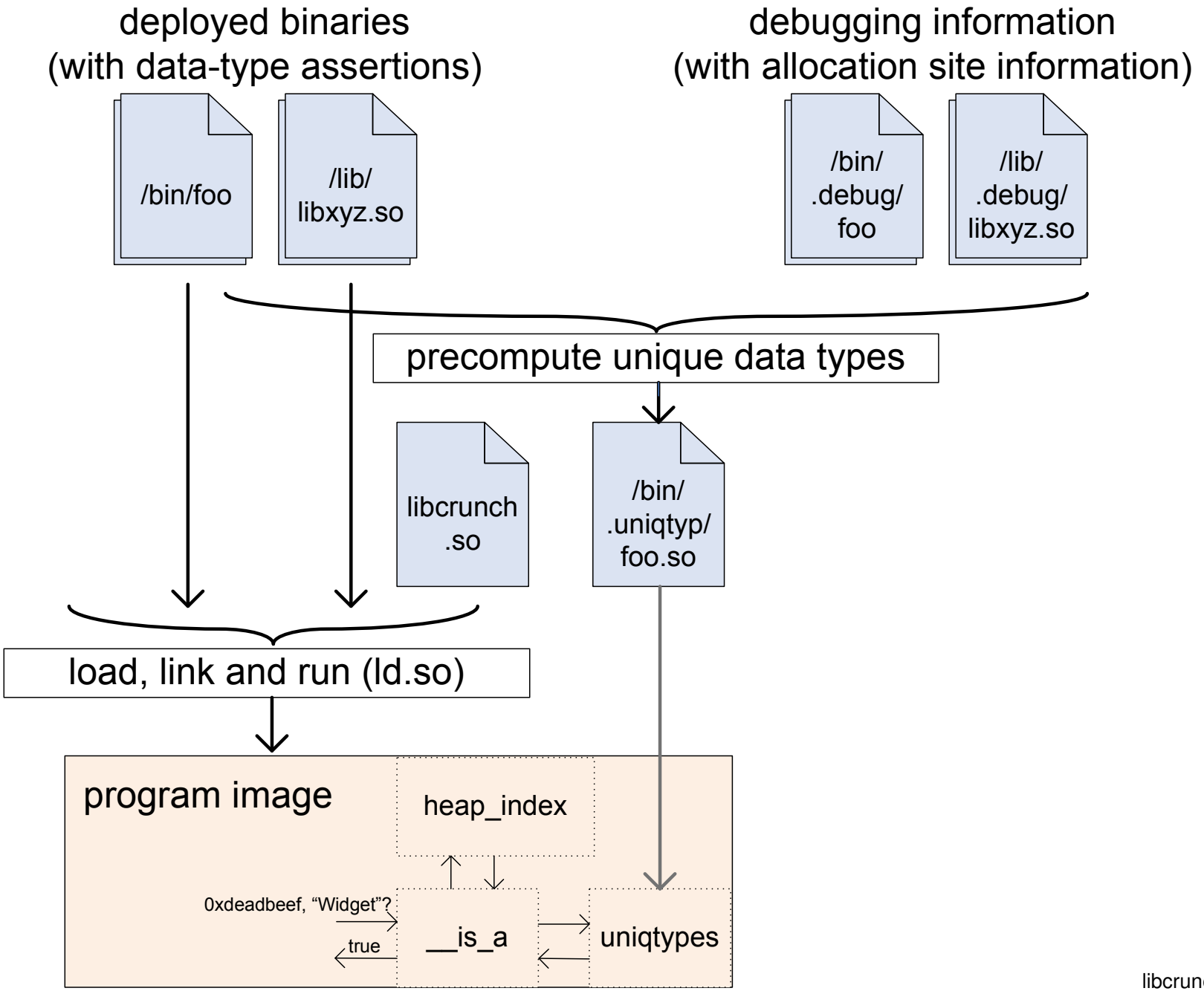
How it works, in a nutshell

```
if (obj->type == OBJ_COMMIT) {
    if (process_commit(walker,
            (assert(__is_a(obj, "struct commit")),
                (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



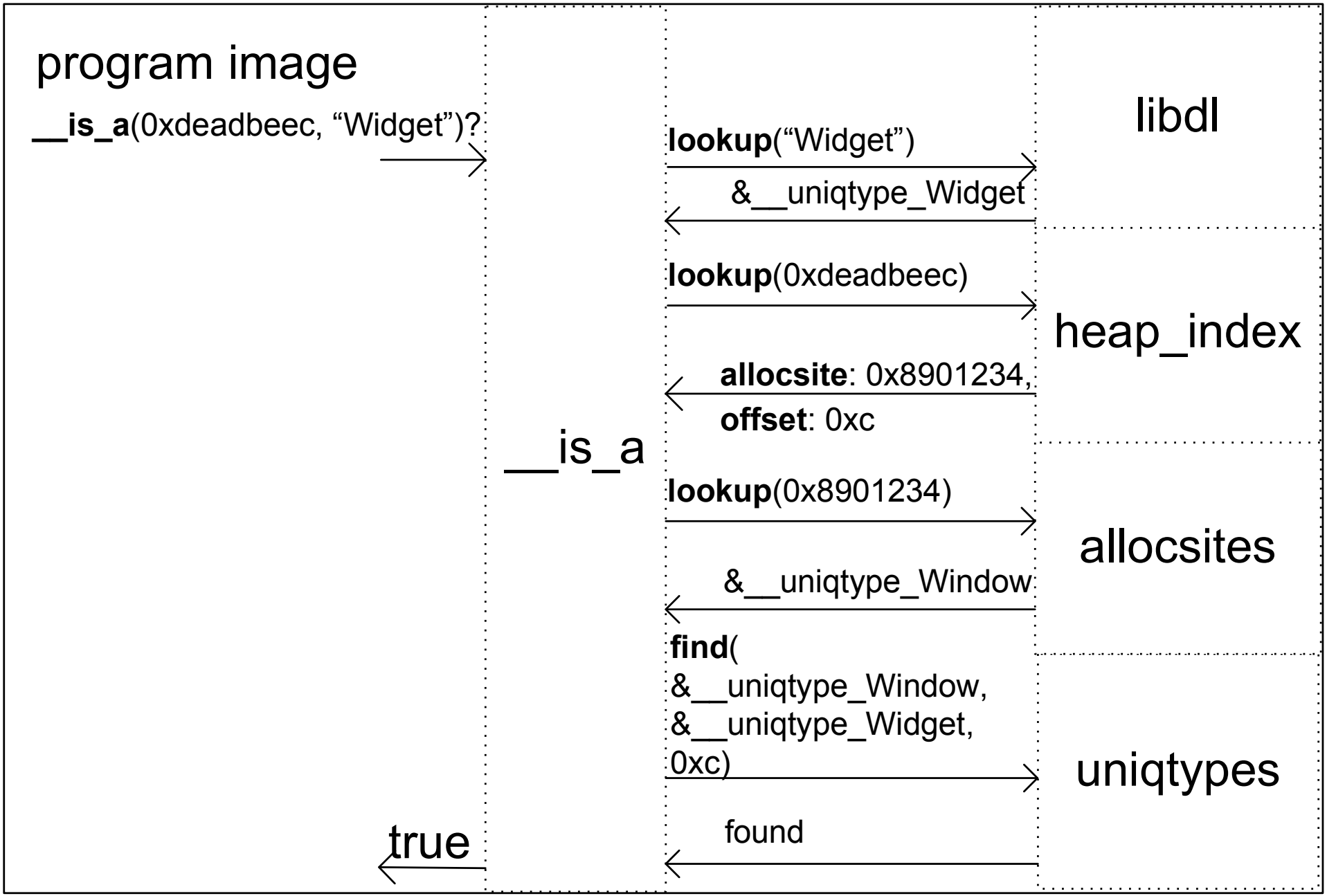
Type info for each allocation

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?



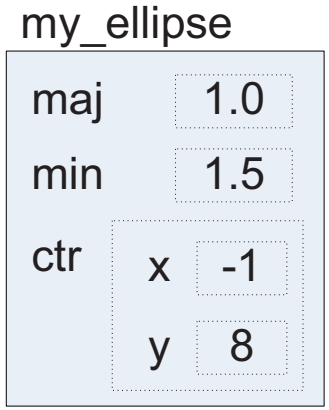
Looking up object metadata (1)

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

- . . . given an arbitrary pointer
- stack case: walk the stack, use debug info
- static case: use debug info
- heap case: hard! might be an *interior* pointer

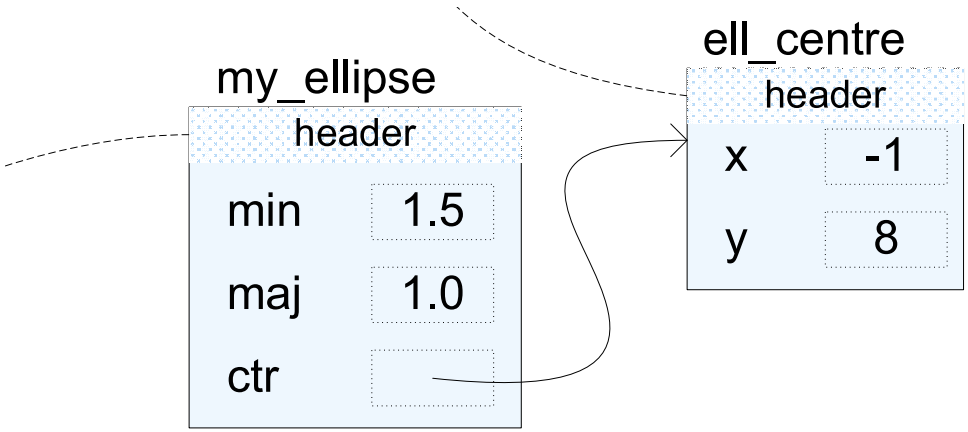
Looking up object metadata (2)

Why the heap case is difficult:




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

Native objects are trees; no descriptive headers! Contrast:



VM-style objects: “no interior pointers”

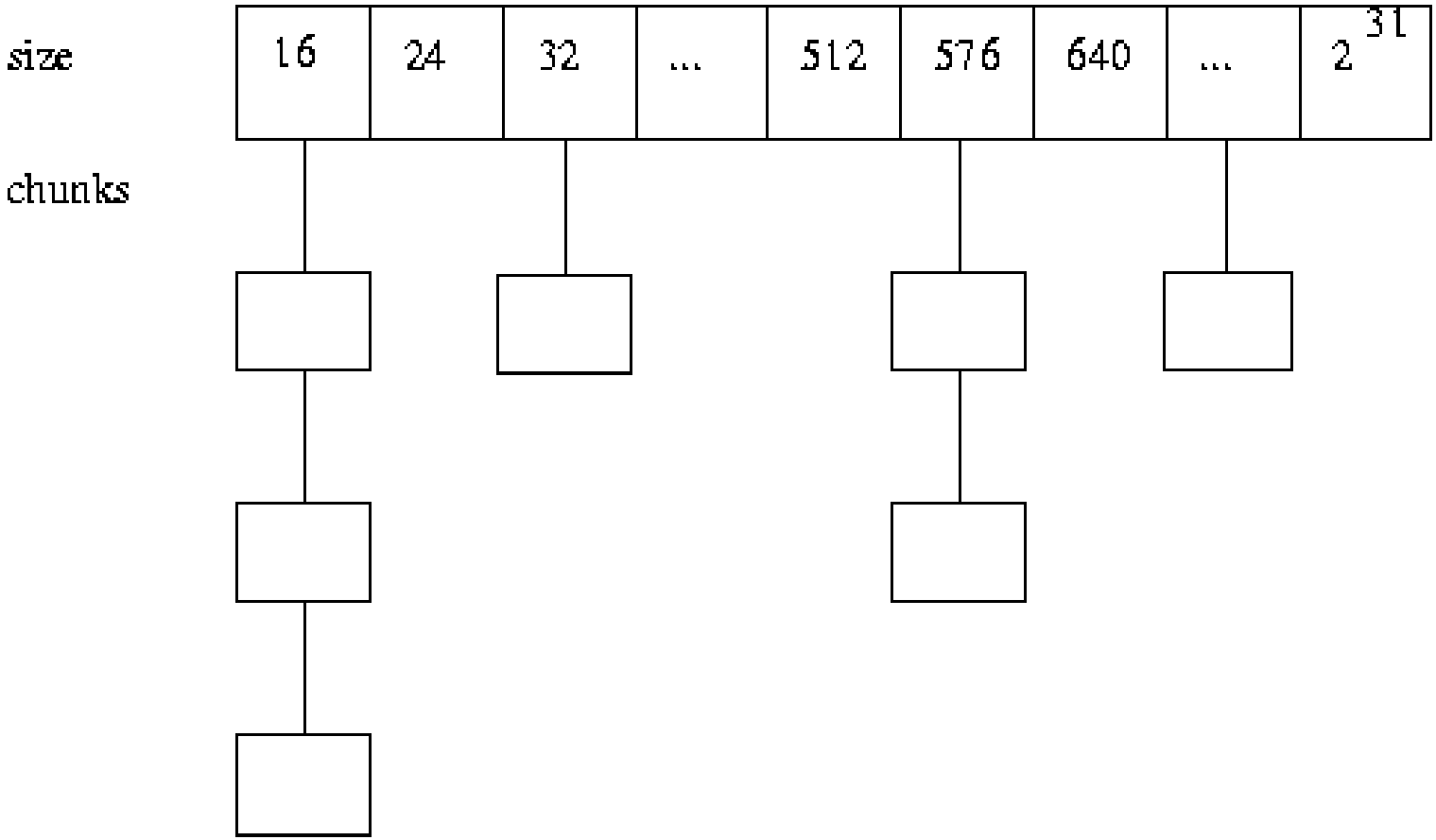
Looking up object metadata (3)

Solution in the heap (difficult) case:

- we'll need some malloc() hooks...
- which keep an *index* of the heap
- in a *memtable*—efficient *address-keyed* associative map
- storing object's *allocation site*
- look up corresponding *data type* later

Indexing chunks

Inspired by free chunk binning in Doug Lea's malloc...



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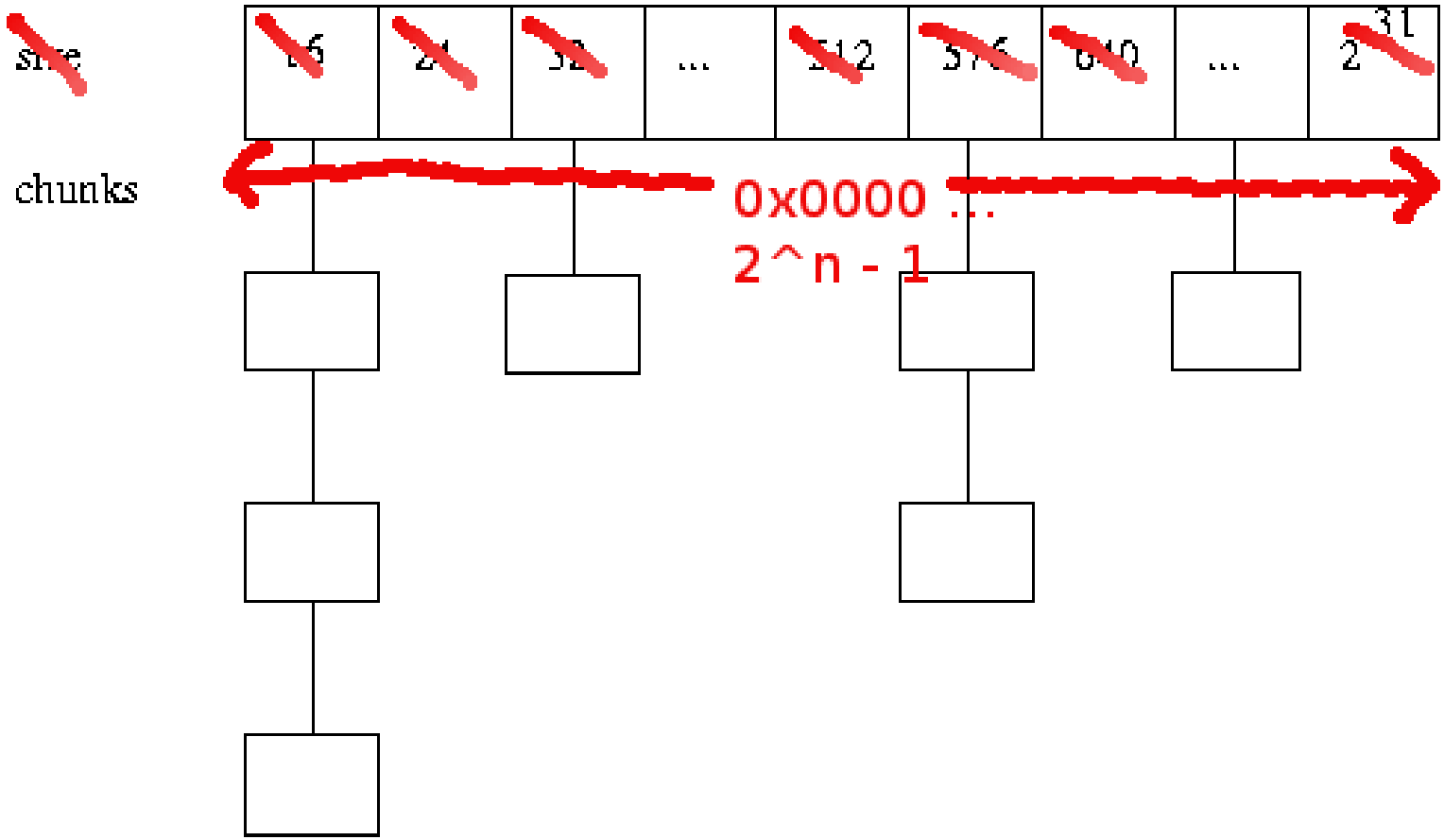


. . . but index *allocated* chunks binned by *address*

How many bins?

Each bin is a linked list of heap chunks

- thread next/prev pointers through allocated chunks...
- also store allocation site addr
- overhead per chunk: one word + two bytes

Finding chunk is $O(n)$ given bin of size n

- $\rightarrow$ want bins to be as small as possible
- Q: how many bins can we have?
- A: lots... really, ***lots***!

Really, how big?

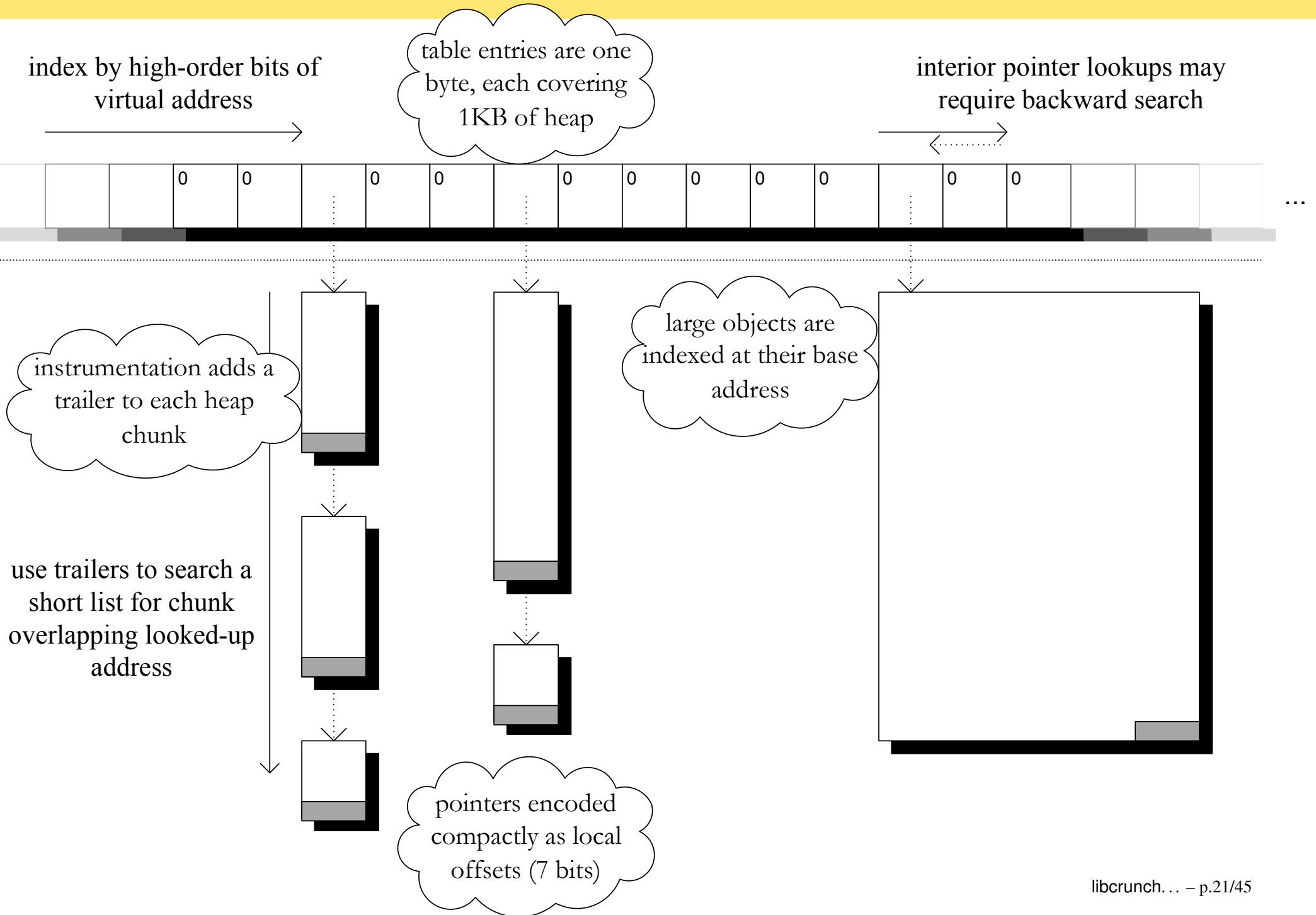
Bin index resembles a linear page table. Exploit

- sparseness of address space usage
- lazy memory commit on “modern OSes” (Linux)

Reasonable tuning for Intel architectures:

- one bin covers 512 bytes of VAS
- each bin’s head pointer takes one byte in the index
- covering n-bit AS requires 2^{n-9}-byte bin index

Big picture of our heap memtable



More about memtables

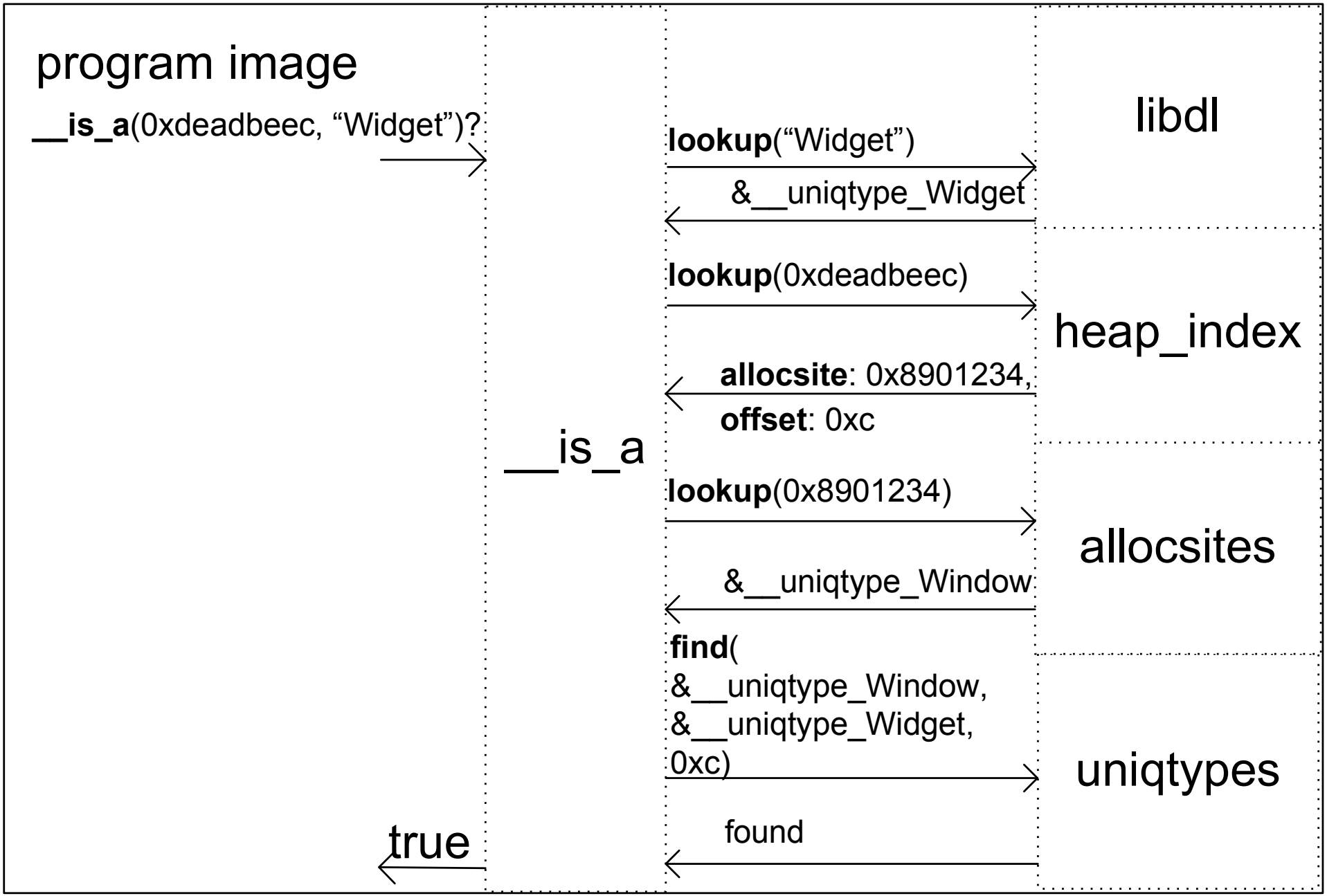
Indexing the heap with a memtable is

- more VAS-efficient than shadow space (SoftBound)
- supports > 1 index, unlike placement-based approaches

Memtables are versatile

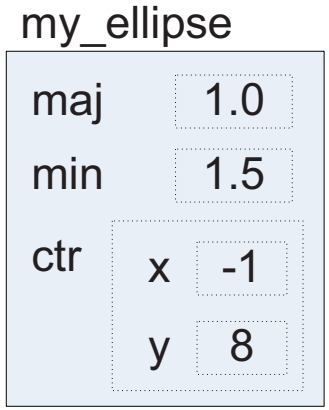
- buckets don't have to be linked lists
- can tune size / coverage...

Remind me: what happens at run time?



__is_a, containment...

A pointer might satisfy __is_a > 1 way




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

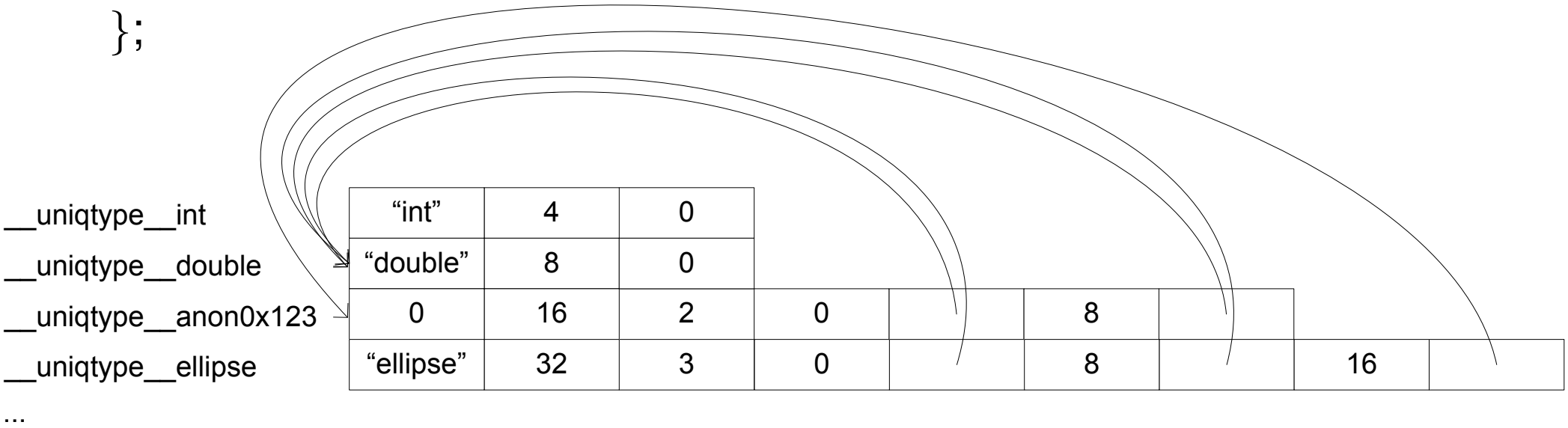
Consider "what is"

- &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 ;
};
```



Reify data types *uniquely*, describing *containment*

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

Precompute this for speed (using make!)

Other flavours of check

__is_a is a nominal check, but we can also write

- __like_a – "structural" (unwrap one level)
- __refines – padded open unions (à la sockaddr)
- __named_a – opaque workaround

Notes about memory safety

We do nothing about memory safety! 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

Recap

What we've just seen is

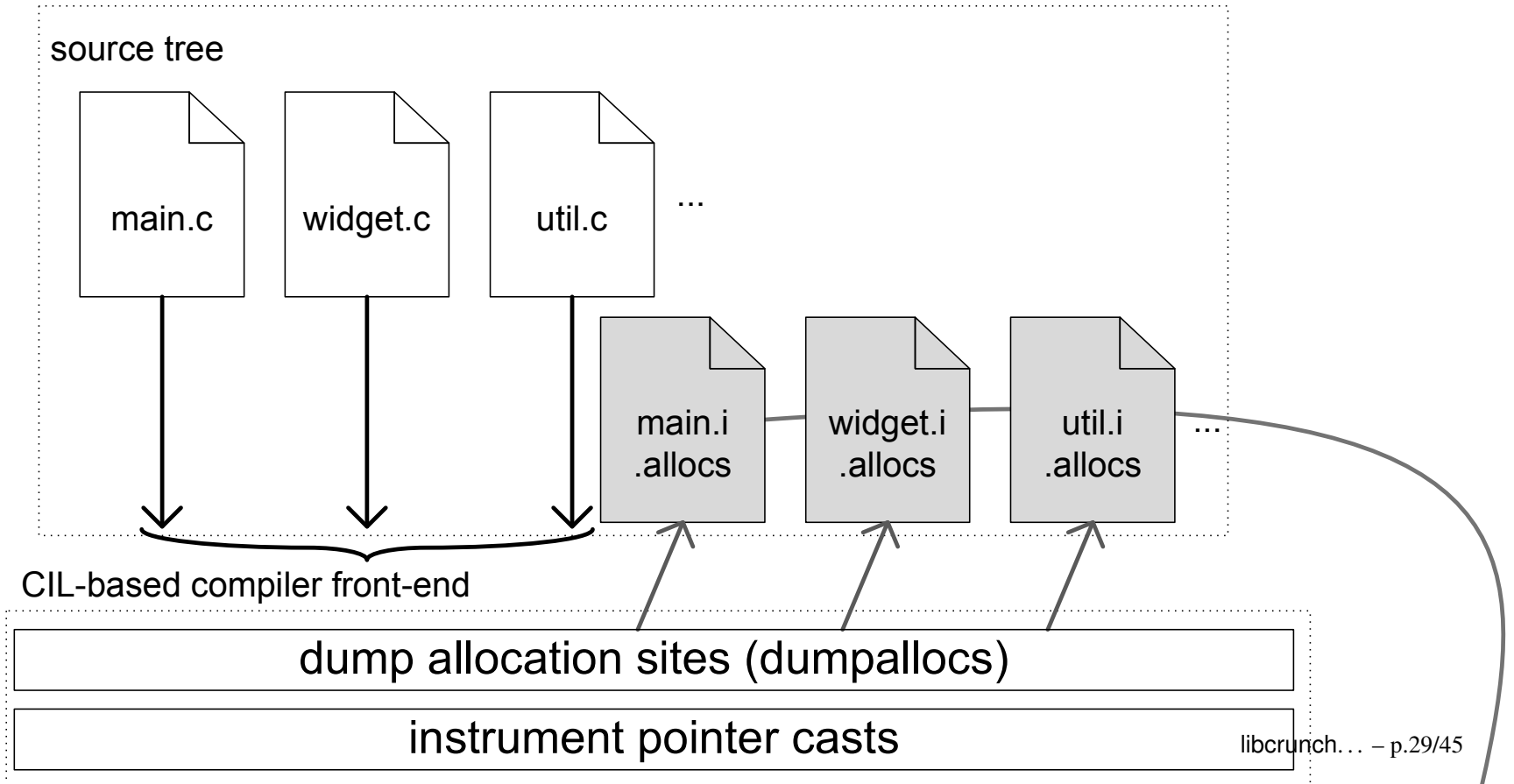
- a runtime system for evaluating type assertions
- fast
- flexible
- a "whole program" design
- language-neutral
- binary compatible

What about *source* compatibility?

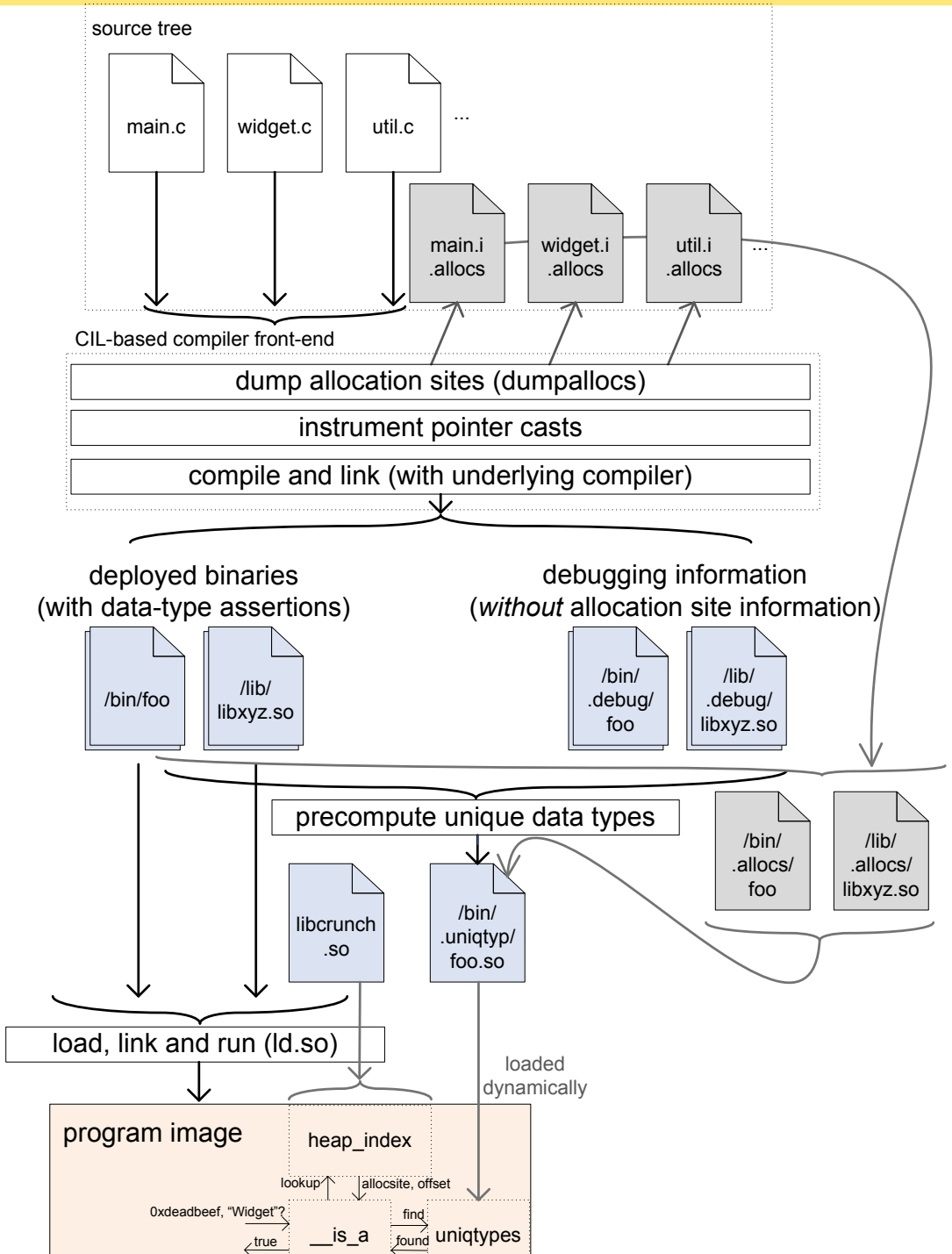
libcrunch prototype: C front-end

Who inserts the assertions?

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



A quick peek at the full picture



Complications (1)

Complications (2)

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 (3)

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

- weird uses of `sizeof`
- weird avoidance of `sizeof`
- redefinition of “the same” data type: use `__like_a`
- casts to incomplete data types: use `__named_a`
- `char` special case
- object re-use
- unions (sometimes okay)
- address-taken union arms

How fast is it?

Performance results go here!

Very quick experiment measuring: heap overhead:

- run gcc on a large C file
- . . . with/without malloc instrumentation
- times in seconds (three runs each):
- gcc + no-op hooks: 1.73, 1.76, 1.72
- gcc + vgHash index: 1.83, 1.82, 1.85
- gcc + memtable index: 1.77, 1.78, 1.77

A story about multiple languages

Imagine a world where

- data structures can be shared
- . . . among code in different languages
- object representations are not “owned” by language
- (“How?” is a separate talk.)

Different invariants make sense for different languages. . .

Enforcing an invariant with libcrunch (1)

Subtle question: what *invariant* do we want to maintain?

- for C: storage has an *allocated* data type
- . . . including *pointer contracts*

```
struct blah {
        int something;
        struct foo *my_foo; // always points to a foo! (or null)
};
```

- allows us to do

```
x = p->q->r;
```

without check.

This is good for C. . .

Enforcing an invariant with libcrunch (2)

In multi-language scenarios we may not have this invariant

- e.g. Python sharing data structures with C
- to be safe, our

  ```
  x = p->q->r;
  ```

  might need extra checks

Invariants on shared data are a shared concern

- e.g. C instrumentor must be more paranoid
- future work to support this
- an exercise in assume–guarantee between languages

Generality: an assertion about assertions

All "type checks" can be encoded as assertions...

```
void swap(void *a, void *b, size_t size)
{
  /* Unconstrained parametric polymorphism */
  assert(typeof(a) == typeof(b));
}
```

... over a suitably *augmented* program.

So much for run time

Type checkers are useful, *but* suffer some problems:

- specification language is distinct and complex
- sometimes incomprehensible error messages
- inflexible
- hard to reason across languages
- can't easily add new kinds of check

Can we *extend* run-time checking *towards* compile time?

Symbolic execution: the Noddy story (1)

"Let input be x; run for all inputs at once."

```
int main(int argc, char **argv) { // ... where argv[1] is symbolic
  assume(argc > 1 && strlen(argv[1]) == 2); // for simplicity
  int temp1 = atoi(argv[1]);
}
```

After this function, temp1 has symbolic value:

```
(Add w32
 (Mul w32 10 (Sub w32 48 (SExt w32 (Read w8 0 argv_1))))
 (Sub w32 48 (SExt w32 (Read w8 1 argv_1))))
```

Execution is

- *deferred*, w.r.t. program values
- *exploratory*, w.r.t. program paths

Symbolic execution: the Noddy story (2)

SE is a *general* forward (sp) analysis:

- program state includes "symbolic variables"…
- …constrained by branches taken so far
- constraints are SMT formulae
- branching exploration of state space
- usu. maximally path- (and "heap-") sensitive

Popular application: bug finding ("test case generation")

- log feasible failures; solver can generate test input
- usually runs forever…

Extending libcrunch towards compile time (1)

Symbolic execution tools only find errors that are

- generic, or. . .
- . . . programmer-supplied: assert()

libcrunch has expanded our specification language!

- i.e. assert() not just over program variables!
- use __is_a() to assert about allocation types

Extending libcrunch towards compile time (2)

Use symbolic execution to "accelerate" dynamic checking!

- start from our run-time checker
- adding exploratoriness (path-sensitivity) via SE
- . . . with tunable proof burden on the user
- (i.e. not-provably-true checks are "left in")

Challenge: scalability. Need an *abstraction* technique.

Reconstructing type checking

```
void *expensive(void *arg); // no type signature!
if (runExpensive) { outputStr = expensive(); }

else { outputStr = "(not done)"; }

assert(is_a(outputStr, "char"));
printf ("Status: %s\n", outputStr);
```

Want to avoid expensive(); how?

- signatures (what type checkers do)

Reconstructing type checking

```
void *expensive(void *arg); // no type sig, but now have summary
if (runExpensive) { outputStr = expensive();
                    typeof(outputStr) = "char"; // from summary
else   { outputStr = "(not done)";
         typeof(outputStr) = "char"; }
assert(typeof(outputStr) == "char");
printf ("Status: %s\n", outputStr);
```

Want to avoid expensive(); how?

- signatures (what type checkers have)
- summaries (their generalisation to SE)

Reconstructing type checking

```
if (runExpensive) {
                    typeof(outputStr) = "char";  // from summary
else    {
          typeof(outputStr) = "char";  }
assert(typeof(outputStr) == "char");
//  printf ()  sliced  away
```

Want to avoid expensive(); how?

- signatures (what type checkers have)
- summaries (their generalisation to SE)

To check *just* the assertions:

- slice on the assertion condition!

Recap, conclusions

We've seen

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

Challenges for the run-time part:

- encode more complex specifications (types)
- make configurable for multiple languages

Challenges for the "towards static" part:

- make it work, make it scale, ...

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

Thanks for listening. Questions?

The story so far

We've seen two possibly-fruitful techniques

- symbolic execution + shadow instrumentation
  - SE "accelerates" dynamic analysis
- slicing on assertion conditions
  - slicing abstracts from "program" to "checker"

Neither is clearly static nor dynamic analysis. What's good:

- programmer-friendly specifications,
- compositional: many shadows can co-exist
- analysability is a property of program, not language
- scope for tuning the precision of analysis

Challenges

Challenges:

- make it work!
- make it terminate
- DSL for specifying new shadow domains?
- integrating with dynamic compilation infrastructure

Scalability is determined by *dependency structure*

- i.e. complexity of dependency…
- …between shadow and program values
- …not on program or specification *language*!

Thanks for listening. Questions?

Agenda

"Program-level type checking"

- not "type-level programming"!

Decouple specification (type assertions)

- from verification algorithm (checker)

Specify a wide range of interesting stuff

- types are one kind of *shadow* ($\approx$ ghosts)

The burden of static typing isn't annotations!

- it's syntactic regularity

Type correctness versus memory correctness

Memory correctness

- has some nice recent work (Softbound + CETS)
- per-pointer metadata $\rightarrow$ slower at run time

My take:

- memory-incorrect programs are also type-incorrect
- converse is not true!
- in this work, I just deal with type correctness

Generalised structural checking

(draw a tree on the whiteboard, please)

Invariants – a ramble-to-self

So far, fully instrumented, what invariant do we get?

- nominal typing
- stored pointers point to their allocated type (or null)
- . . . precisely! but
- subtyping is a non-issue!
- e.g. encoding subtyping as zero-offset containment "just works"
- and multiple inheritance works, given that adjustment is done explicitly
- the invariant holds as a consequence of the semantics of C!
- pointer loads: may be passed through cast

- on the target of pointers (to pointers (to pointers. . .
- we only check the first level of indirection immediately
- . . . and rely on the invariant to guarantee us the rest
- e.g. consider `b = (char **) x;`
- This checks that `x` points to something
- that was *allocated as* a `char *`.
- we have maintained the invariant that if it was allocated as a `char *`, it still respects that invariant, i.e. points to a `char` (or null)
- so, we don't need to do check that chase pointers / explore the heap
- (anyone want to formalise this?)
- If we didn't maintain this invariant, i.e. we allowed pointers declared as `char*` to actually point to `int`, we would have a harder problem.
- it's okay if we have just Python, say, and every reference is (effectively) `void*`

- it's a problem if we allow Python to manipulate C-allocated data structures
- they will claim to store an `int*`
- but Python may have updated it to point to a `Foo`!
- e.g. if we allowed C dta