Run-time type checking of whole programs

and other stories ■ .

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        return -1;
    return 0;
}
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- binary-compatible
- source-compatible
- reasonable performance
- avoid being C-specific!*

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... in fact, a general-purpose "dynamic" run-time (ask me)

The main part of this talk in one slide

I describe libcrunch, which is

- an infrastructure for run-time type checking
- encodes type checks as assertions over reified data types
- per-language front-ends (C; C++, Fortran, . . .)
- support idiomatic unsafe code, unmodified*
- target: safe *assuming memory safety*
- no binary interface changes

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

Why care about unsafe languages?

- fine control of resource utilisation
- talk directly to operating system
- talk directly to hardware
- freedom to {simulate, violate} abstractions
- re-use existing code (a *huge* investment)
- unsafe is the “hard / general” case

What is “type-correctness”?

“Type” means “data type”

- instantiate = allocate
- concerns storage
- “correct”: reads and writes respect allocated data type
- cf. *memory*-correct (spatial, temporal)

Languages can be “safe”; programs can be “correct”

The user's eye view

- `$ crunchcc -o myprog ...   # + other front-ends`

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- `$ ./myprog  # runs normally`
- `$ LD_PRELOAD=libcrunch.so ./myprog # does checks`
- `myprog: Failed __is_a_internal(0x5a1220, 0x413560 a.k.a. "uint$32") at 0x40dade, allocation was a heap block of int$32 originating at 0x40daa1`

How it works for C code, in a nutshell

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

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

How it works for C code, 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 for C code, 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;
}
```

Want a runtime with magical powers

- tracking *allocations*
- with type info
- efficiently
- → fast __is_a() function

What does a C compiler *not* check?

```
int a = 1;
char *b = ...;
void f(double);

f(a);              // okay -- compiler adds conversion
b = a;             // not okay -- compiler tells us
f(b);              // not okay -- compiler tells us
f(*(double*)b);    // depends...
```

Want to check what the compiler punts on

- use of pointers ("distant" accesses)
- also (rarer): unions, varargs functions

Memory-correctness vs type-correctness (1)

Pointer-y things checked by existing tools

- spatial m-c – bounds (SoftBound, Asan)
- temporal$_1$ m-c – use-after-free (CETS, Asan)
- temporal$_2$ m-c – initializedness (Memcheck, Msan)
- nothing to do with types!

Slow!

- metadata per {value, pointer}
- check on use

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- nothing to do with types!

~~Slow!~~ Faster:

- metadata per ~~{value, pointer}~~ allocation
- check on ~~use~~ create

```
// a check over object metadata... guards creation of the pointer
(assert( __is_a (obj, "struct commit")), (struct commit *)obj)
```

Memory-correctness vs type-correctness (2)

For now, *assume* memory-correct execution

- "also use one of those other tools"

Then do only the additional checks s.t.

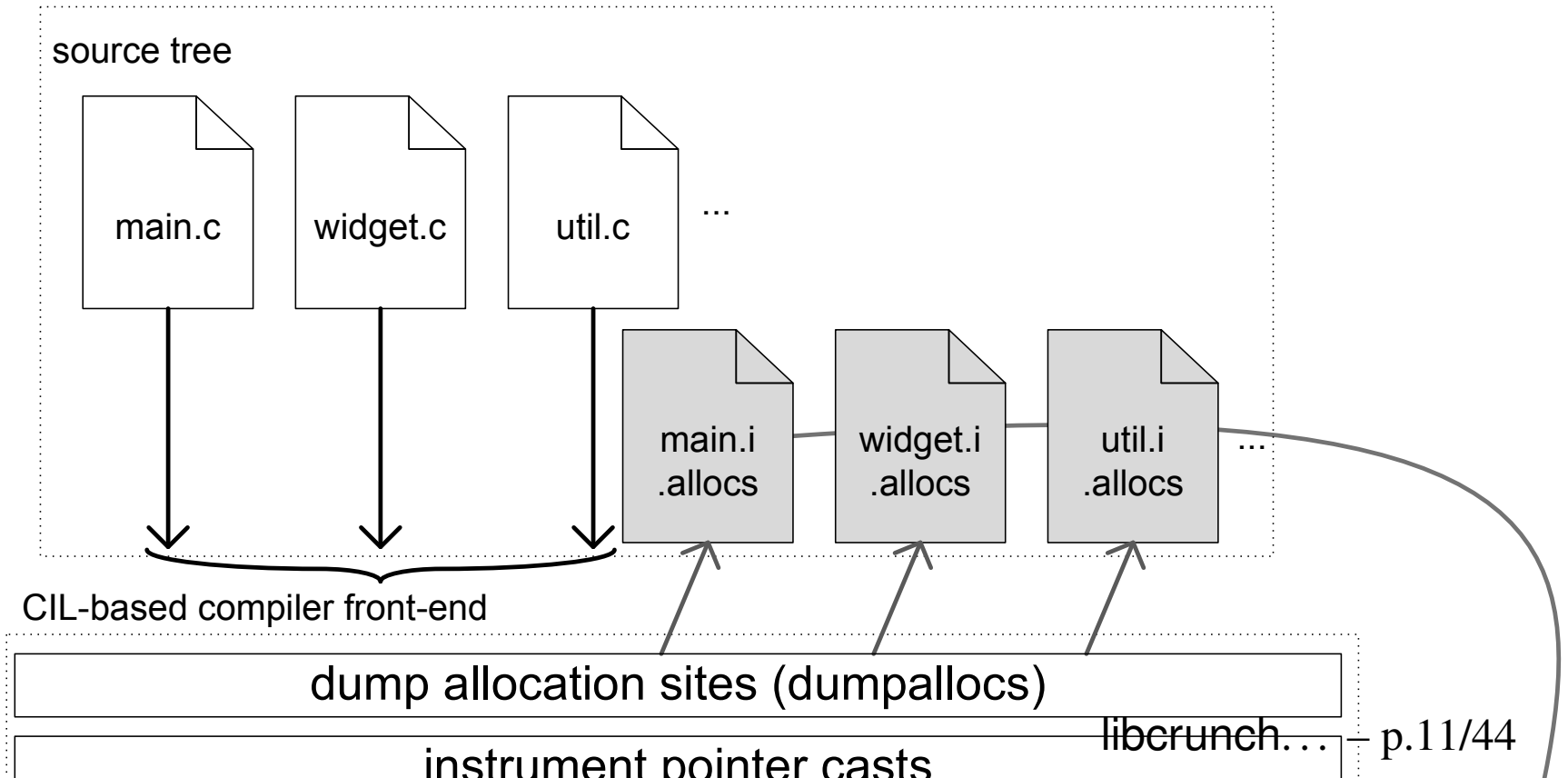
- all memory accesses respect memory's *allocated type*

. . . which, for C, can be done by maintaining an invariant:

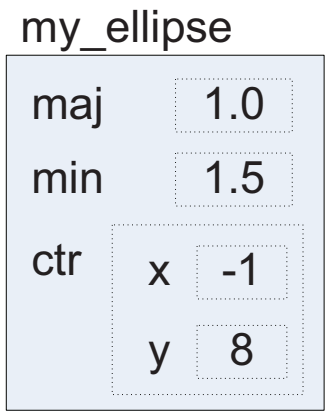
- every live pointer respects its *contract* (pointee type)
- must also check unsafe loads/stores *not* via pointers
  - unions, varargs

What data type is being malloc()'d?

- . . . guess from use of sizeof
- dump *typed allocation sites* from compiler
- guessing is moderately clever
  - e.g. malloc(sizeof (Blah) + n * sizeof (Foo))



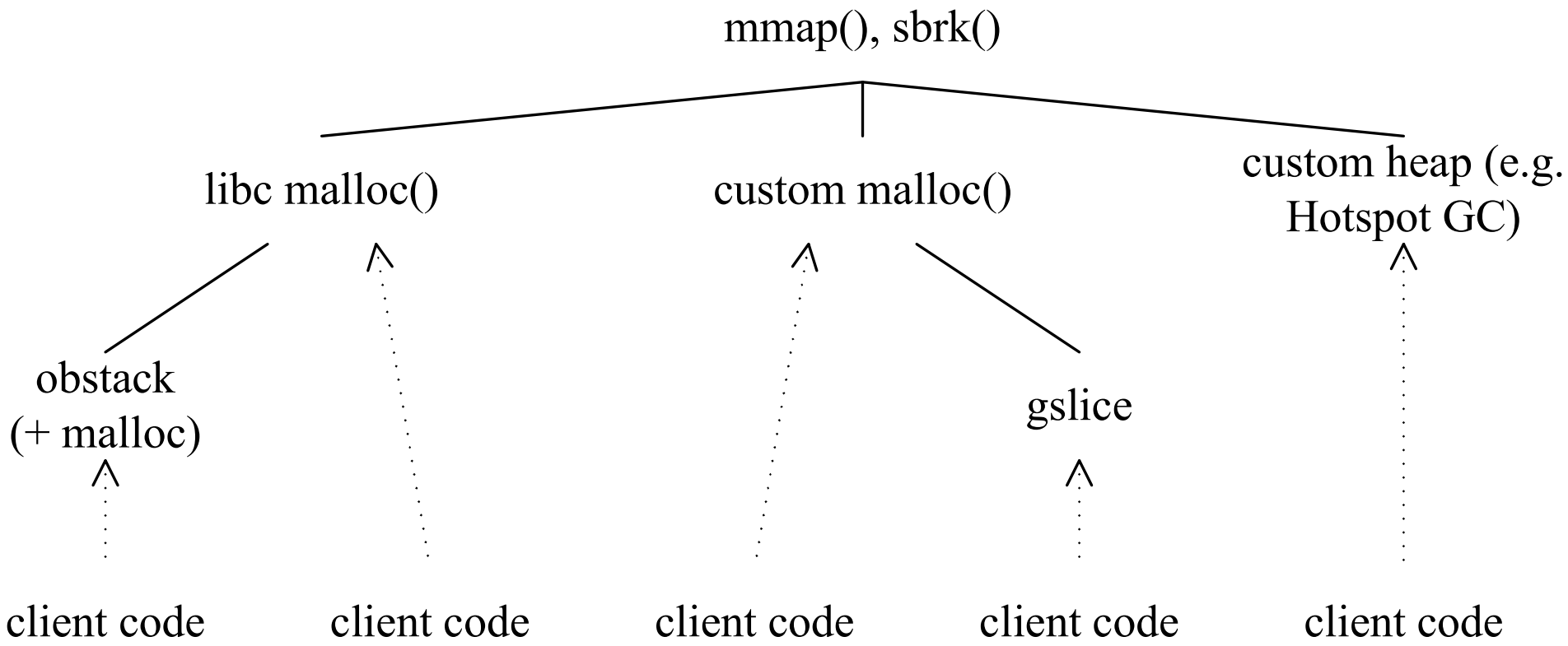
Non-difficulties




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

- structure “subtyping” via containment
- function pointers (most of the time)
- void pointers
- char pointers
- integer $\leftrightarrow$ pointer casts
- type-differing aliases
- custom allocators, memory pools etc.

Hierarchical model of allocations



Somewhat difficult cases

Solved:

- opaque types
- complex use of sizeof
- structure “subtyping” via prefixing

Give up:

- avoidance of sizeof
- address-taken union members
- non-procedurally abstracted object allocation/re-use

The remaining awkwards

- alloca
- unions
- varargs
- generic use of non-generic pointers (void**, . . .)
- casts of function pointers *to non-supertypes*

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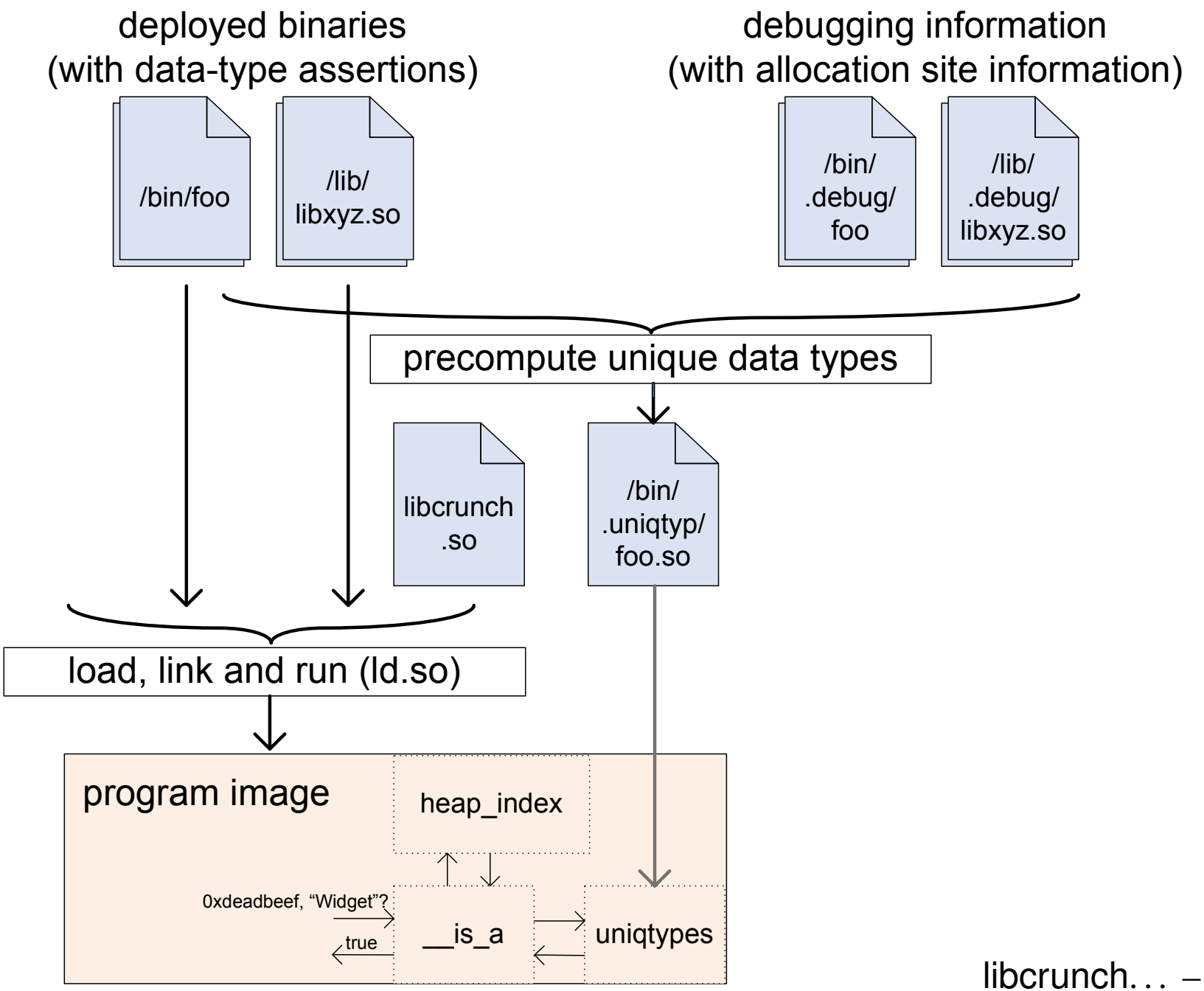
All solved/solvable with some extra instrumentation

- supply our own alloca
- instrument writes to unions
- instrument calls via varargs lvalues; use own va_arg
- instrument writes through void** (check invariant!)
- optionally instr. *all* indirect calls

Idealised view of libcrunch toolchain



A model of data types: DWARF debugging info

```
$ cc -g -o hello hello.c && readelf -wi hello | column
 <b>:TAG_compile_unit                  <7ae>:TAG_pointer_type
      AT_language  : 1 (ANSI C)             AT_byte_size: 8
      AT_name      : hello.c                AT_type     : <0x2af>
      AT_low_pc    : 0x4004f4          <76c>:TAG_subprogram
      AT_high_pc   : 0x400514               AT_name     : main
 <c5>: TAG_base_type                        AT_type     : <0xc5>
       AT_byte_size : 4                     AT_low_pc   : 0x4004f4
       AT_encoding  : 5 (signed)            AT_high_pc  : 0x400514
       AT_name      : int               <791>: TAG_formal_parameter
 <2af>:TAG_pointer_type                      AT_name     : argc
       AT_byte_size: 8                       AT_type     : <0xc5>
       AT_type     : <0x2b5>                 AT_location : fbreg - 20
 <2b5>:TAG_base_type                   <79f>: TAG_formal_parameter
       AT_byte_size: 1                       AT_name     : argv
       AT_encoding : 6 (char)                AT_type     : <0x7ae>
       AT_name     : char                    AT_location : fbreg - 32
```

Type info for each allocation

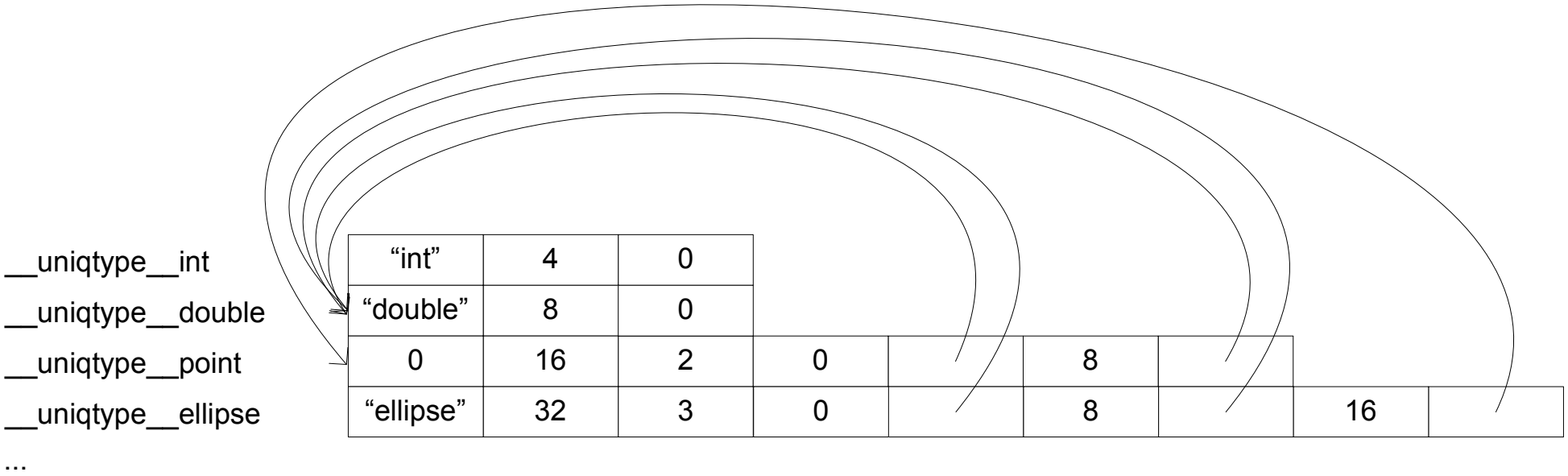
What is an allocation?

- static memory: mmap'd program binaries
- heap memory: "anonymous" mmappings
  - returned by malloc() – "level 1" allocation
  - returned by mmap() – "level 0" allocation
  - (maybe) memory issued by user allocators...
- stack memory

We keep specialised *indexes* for each kind of memory...

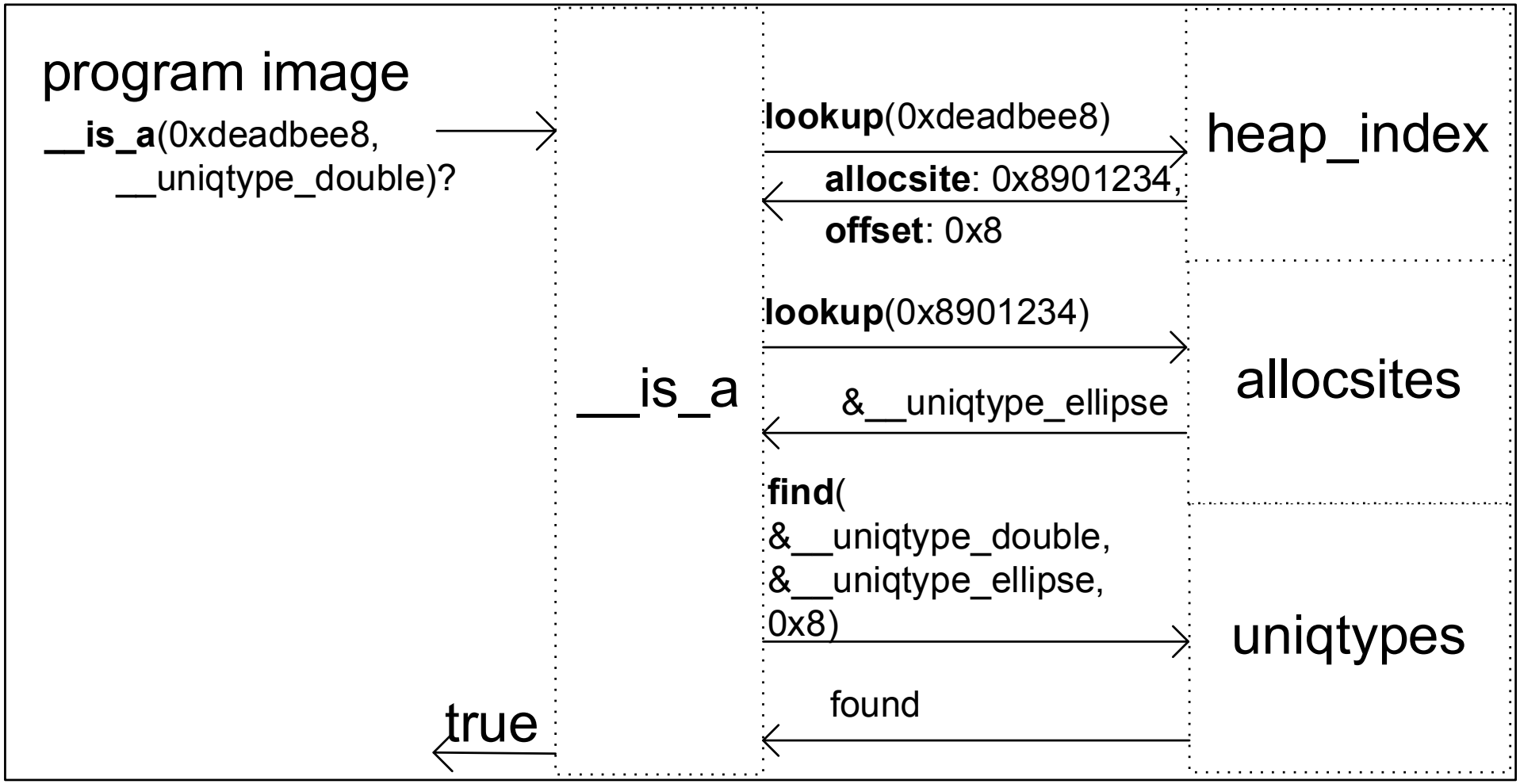
Representation of data types

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



- use the linker to keep them unique
- uniqueness → "exact type" test is a pointer comparison
- __is_a() is a short search

What happens at run time?



Getting from objects to their metadata

Recall: binary & source compatibility requirements

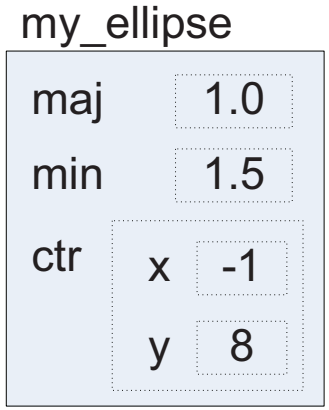
- can't embed metadata into objects
- can't change object layouts at all!
- $\rightarrow$ need out-of-band ("disjoint") metadata

Pointers can point anywhere inside an object

- which may be stack-, static- or heap-allocated

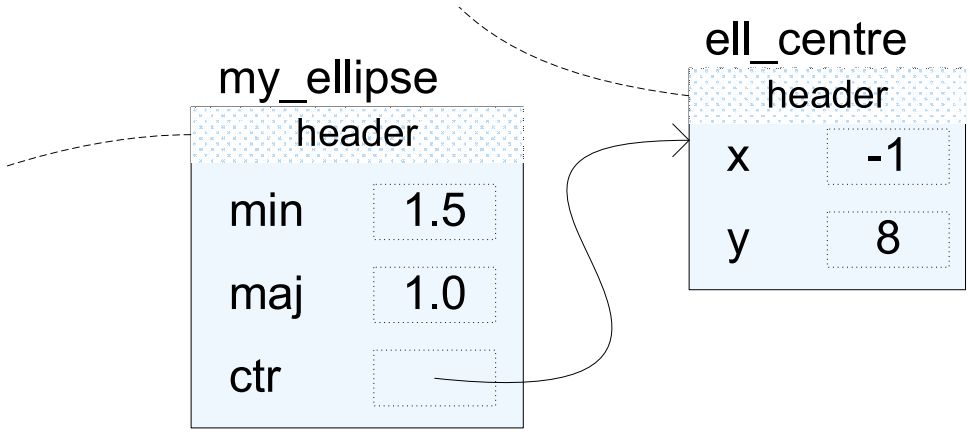
Why the heap case is difficult, cf. virtual machine heaps

Native objects are trees; no descriptive headers!




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

VM-style objects: “no interior pointers”



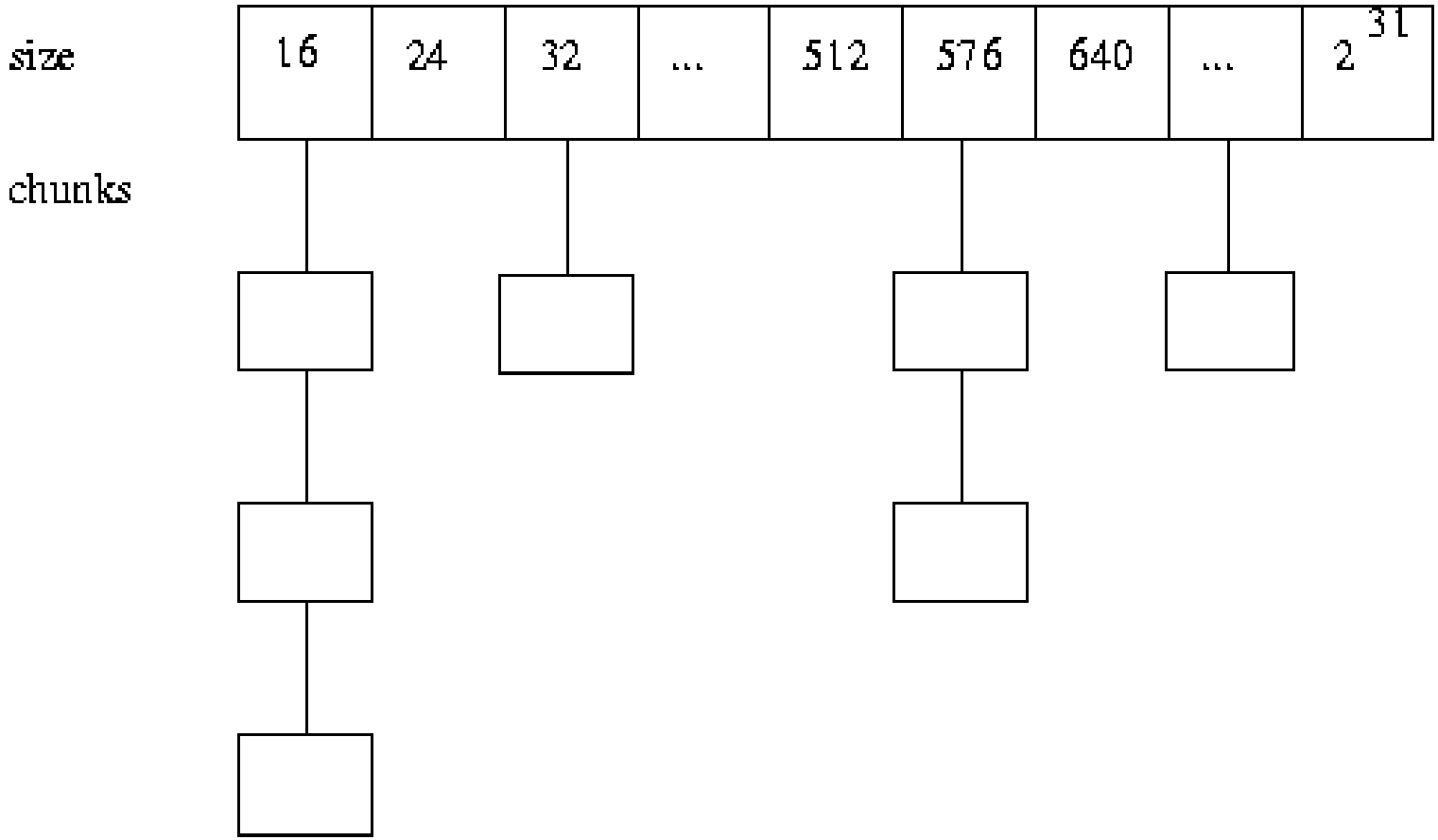
To solve the heap case...

- we'll need some malloc() hooks...
- which keep an *index* of the heap
- in a *memtable*—efficient *address-keyed* associative map
  - must support (some) range queries
- storing object's metadata

Memtables make aggressive use of virtual memory

Indexing heap chunks

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



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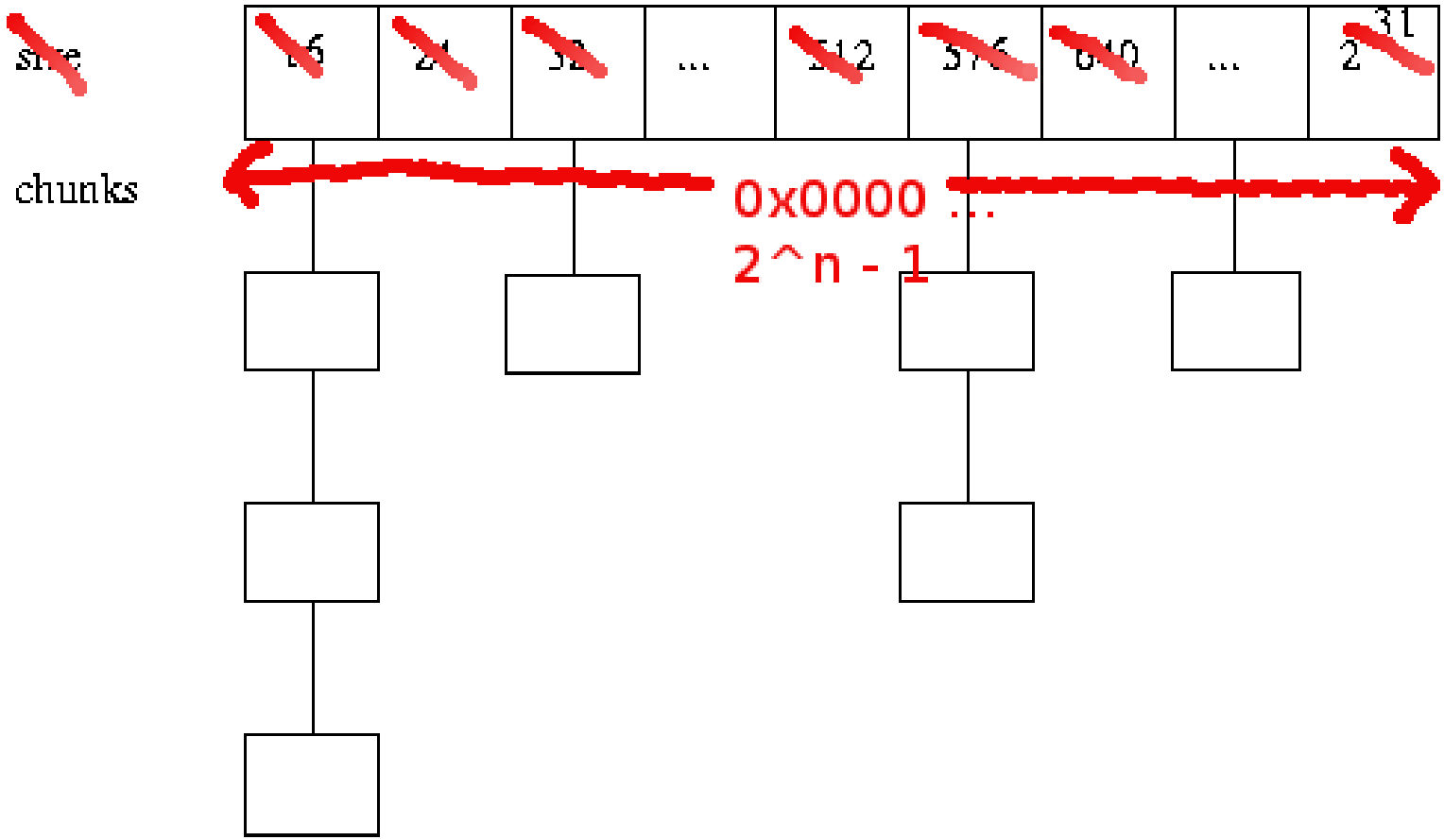


. . . but index *allocated* chunks binned by *address*

How many bins?

Each bin is a linked list of heap chunks

- thread next/prev pointers through allocated chunks...
- also store metadata (allocation site address)
- 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?

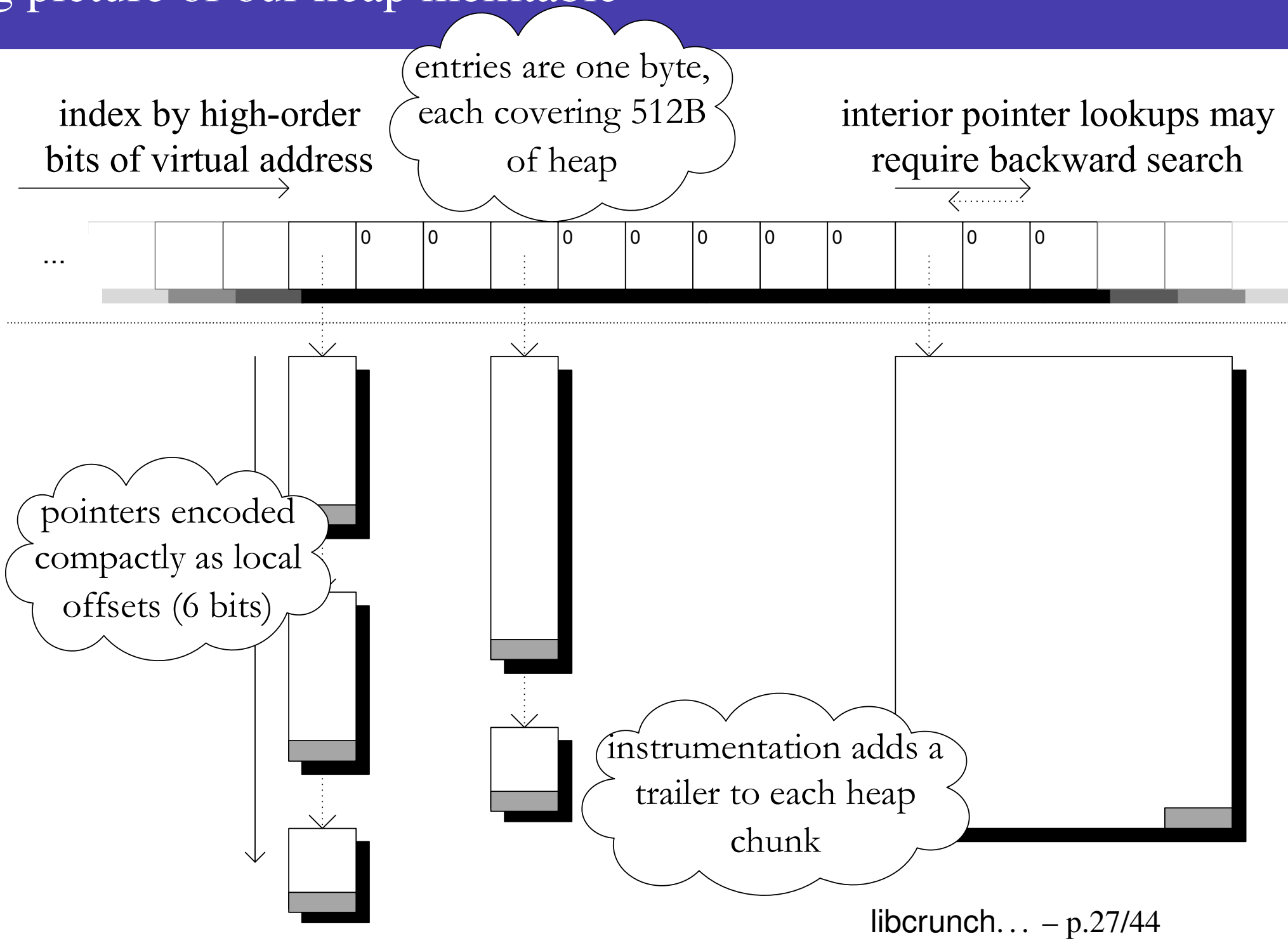
Bin index resembles a linear page table. Exploit

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

Reasonable tuning for malloc heaps on 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



Indexing the heap with a memtable is. . .

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

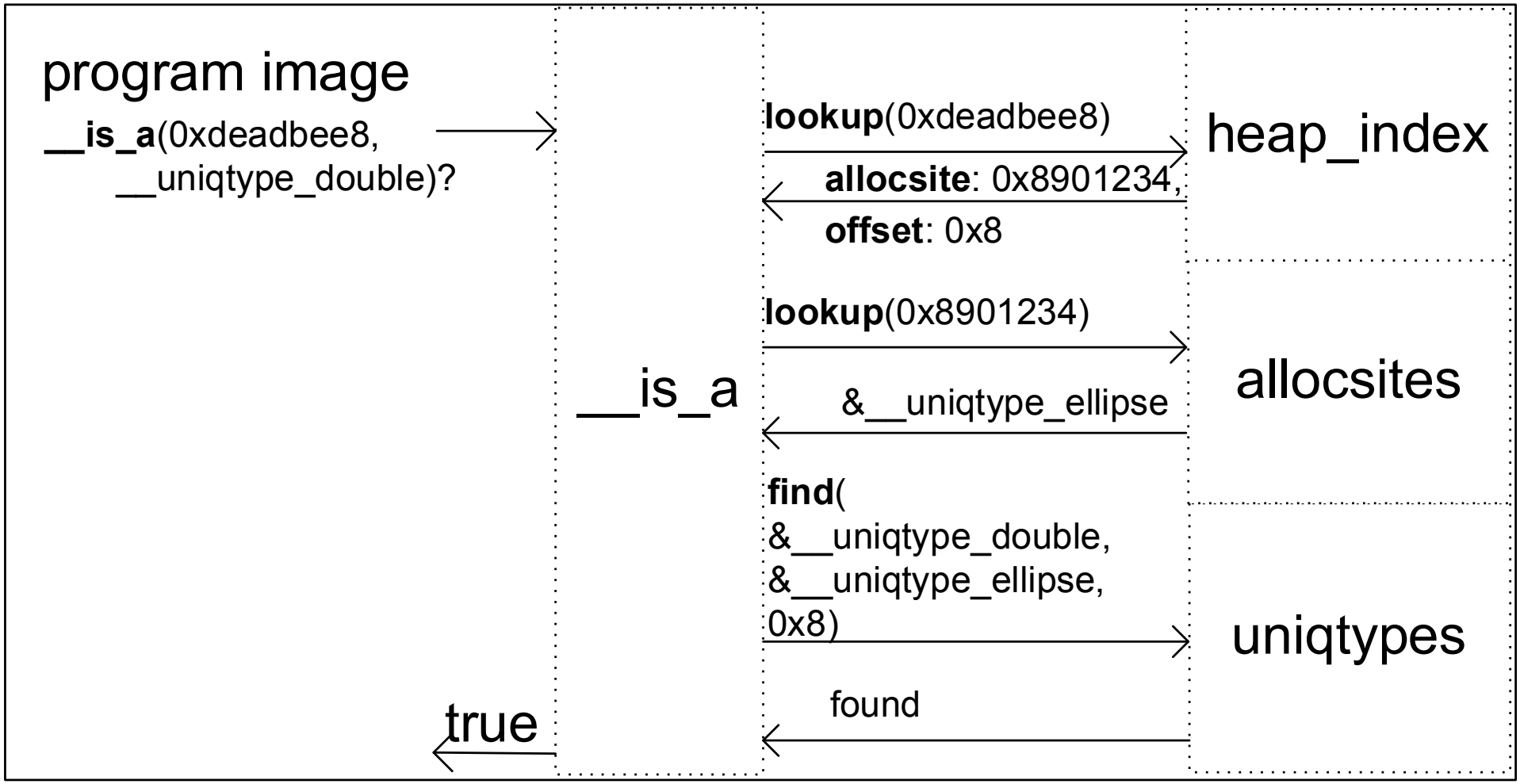
Memtables are versatile

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

We also use memtables to

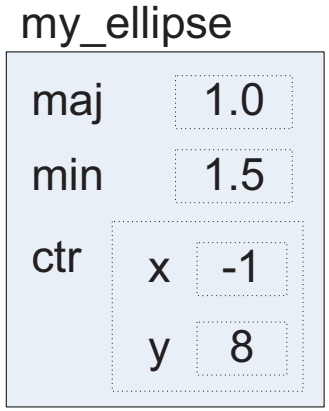
- index every mapped page in the process ("level 0")
- index "deep" (level 2+) allocations
- index static allocations
- index the stack (map PC to frame uniqtype)

Remind me: what happens at run time?



__is_a, containment...

Pointer p might satisfy __is_a(p, T) for T_0, T_1, ...




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

Consider "what is"

- &my_ellipse
- &my_ellipse.ctr
- ...

(Subclassing is usually implemented this way.)

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

. . . or invent your own!

Recap

What we've just seen is

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

What about *source* compatibility?

Link-time interventions

We also interfere with linking:

- link in uniqtypes referred to by each `.o`'s checks
- hook allocation functions
- . . . distinguishing wrappers from "deep" allocators

Currently provide options in environment variables. . .

```
LIBCRUNCH_ALLOC_FNS="xcalloc(zZ) xmalloc(Z) xrealloc(pZ) x
LIBCRUNCH_LAZY_HEAP_TYPES="__PTR_void"
```

How fast is it? SPEC CPU2006 results

benchmark	normal/s	crunch	nopreload	just allocs
perlbench	1.48	+31 %	–	+3%
bzip2	5.05	+0 %	+0%	+0%
mcf	2.49	+6.8%	−1%	+0%
milc	8.75	+38 %	+2%	−1%
gobmk	14.5	+13 %	+1%	+1%
hmmer	2.13	+8.5%	+8%	+0%
sjeng	3.25	−2.2%	−2%	+0%
h264ref	10.0	+5 %	+5%	+1%
lbm	3.43	+24 %	+0%	+0%
sphinx3	1.58	+15 %	+2%	+4%
gcc	0.989	+289 %	–	+4%

Popular errors

- sloppiness about signed vs unsigned
- some user-level allocation behaviour
- some cases of multiple indirection of void

```
void get_obj(struct Foo **out);
void *opaque_obj;
get_obj(&opaque_obj);
```

False negatives:

- memory-incorrect programs
- unions
- over-coarse sloppification (e.g. __like_a)

More case studies needed...

Generic pointers to non-generic pointers

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

Generic pointers to pointers to non-generic pointers

```
PUB_FUNC void dynarray_add(void ***ptab, int *nb_ptr, void *data)
{   /*  ...  */
    /*  every power of two we double array size */
    if ((nb & (nb - 1)) == 0) {
        if (!nb) nb_alloc = 1; else nb_alloc = nb * 2;
        pp = tcc_realloc (pp, nb_alloc * sizeof(void *));
        *ptab = pp;
    }
    /*  ...  */
}
char **libs = NULL;
/*  ...  */
dynarray_add((void ***) &libs, &nblibs, tcc_strdup(filename));
```

Zoo: data stuffing (1)

```
typedef double LBM_Grid[SIZE_Z*SIZE_Y*SIZE_X*N_CELL_ENTRIES];
typedef LBM_Grid* LBM_GridPtr;

#define MAGIC_CAST(v) ((unsigned int*) ((void*) (&(v))))
#define FLAG_VAR(v) unsigned int* const _aux_ = MAGIC_CAST(v)
//   ...
#define TEST_FLAG(g,x,y,z,f)    \
    ((*MAGIC_CAST(GRID_ENTRY(g, x, y, z, FLAGS))) & (f))
#define SET_FLAG(g,x,y,z,f)       \
{FLAG_VAR(GRID_ENTRY(g, x, y, z, FLAGS)); (*_aux_) |= (f);}
```

Zoo: data stuffing (2)

```
#define FUNC_CALL(r) (((AttributeDef*)&(r))->func_call)

typedef struct Sym {
    int v;      /* symbol token */
    long r;     /* associated register */
    long c;     /* associated number */
    CType type;     /* associated type */
    struct Sym *next; /* next related symbol */
    struct Sym *prev; /* prev symbol in stack */
    struct Sym *prev_tok; /* previous symbol for this token */
} Sym;

 func_attr_t *func_call = FUNC_CALL(sym->r);
```

Zoo: pointer stuffing (1)

```
typedef int parse_opt_cb(const struct option *,
        const char *arg, int unset);

static int stdin_cacheinfo_callback(struct parse_opt_ctx_t *ctx,
                                    const struct option *opt, int unset)
{ /* ... */ }

struct option options[] = {
        /* ... */,
        {OPTION_LOWLEVEL_CALLBACK, 0, /* ...*/,
                (parse_opt_cb *) stdin_cacheinfo_callback},
        /* ... */
};
```

Zoo: pointer stuffing (2)

```
if (value->kind > RTX_DOUBLE && value->un.addr.base != 0)
  switch (GET_CODE (value->un.addr.base))
    {
    case SYMBOL_REF:
      /* Use the string's address, not the SYMBOL_REF's address,
          for the sake of addresses of library routines. */
      value->un.addr.base = (rtx) XSTR (value->un.addr.base, 0);
      break;
    /* ... */
    }
```

Zoo: non-observable allocation bugs (1)

```
item->util = xcalloc(sizeof(struct branch_info), 1);
```

Zoo: non-observable allocation bugs (2)

```
if (((* array4D) = (short****)calloc(idx, sizeof(short**))) == NULL)
  no_mem_exit("get_mem4Dshort: array4D");
```

End

Code is here:

- https://github.com/stephenrkell/libcrunch

and also

- https://github.com/stephenrkell/libdwarfpp
- https://github.com/stephenrkell/dwarfidl
- https://github.com/stephenrkell/liballocs
- https://github.com/stephenrkell/libsrk31c++
- . . .
- will make a friendly download-and-build script soon

Questions?