Fast, precise dynamic checking of types and bounds “in C”

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    if (process_commit(walker, (struct commit *)obj))
        return -1;
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- source-compatible
- ... for real, idiomatic code in (say) C
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Enter libcrunch, which does the above.

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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`

Reminiscent of Valgrind (Memcheck), but different...

- not checking memory definedness, in-boundsness, etc..
- ... in fact, *assume correct* w.r.t. these!
- provide & exploit *run-time type information*

Sketch of the instrumentation for C

```
if (obj->type == OBJ_COMMIT) {
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                       (struct commit *)obj))
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Sketch of the instrumentation for C

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                (struct commit *)obj)))
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```
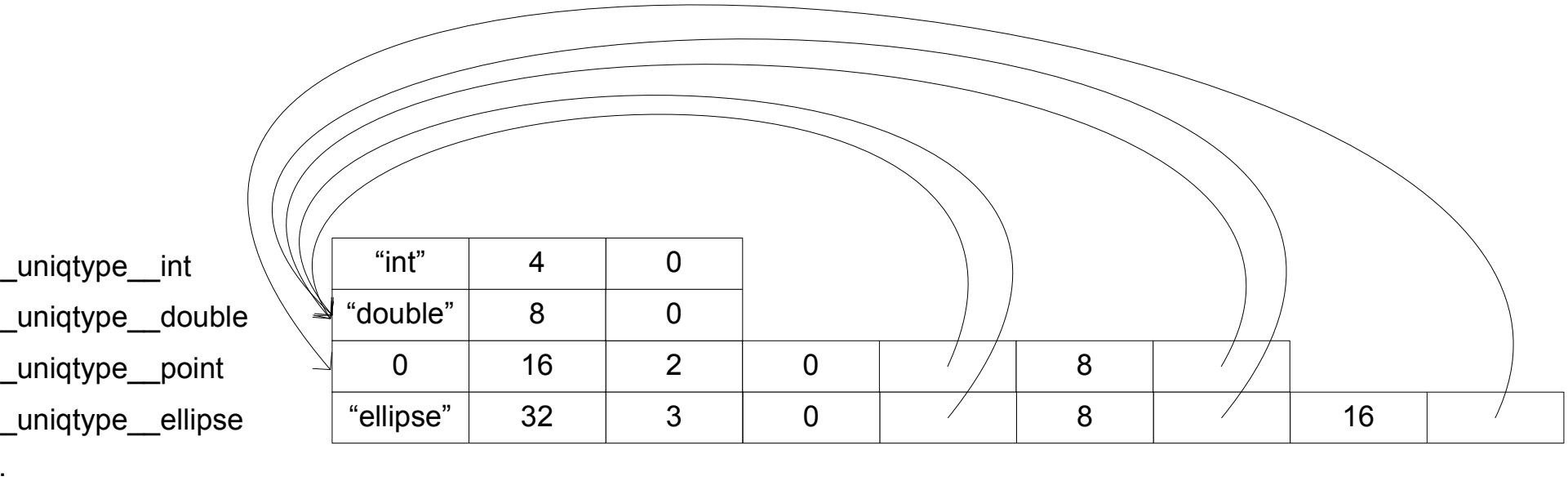

Need a runtime which

- provides a fast __is_a() function
- ... and a few other flavours of check
- by efficiently tracking *allocations*
- ... and attaching reified type info

Reified, unique data types

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



- also model: stack frames, functions, pointers, arrays, . . .
- unique → "exact type" test is a pointer comparison
- __is_a() is a short search over containment edges

Is it really that simple? What about. . . ?

- untyped malloc() et al.
- opaque pointers, a.k.a. void*
- conversion of pointers to integers and back
- function pointers
- pointers to pointers
- "simulated subtyping"
- {custom, nested} heap allocators
- alloca()
- "sloppy" (non-standard-compliant) code
- unions, varargs, memcpy()

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What data type is being malloc()'d?

Use intraprocedural "sizeofness" analysis

```
size_t sz = sizeof (struct Foo);
/* ... */
malloc(sz);
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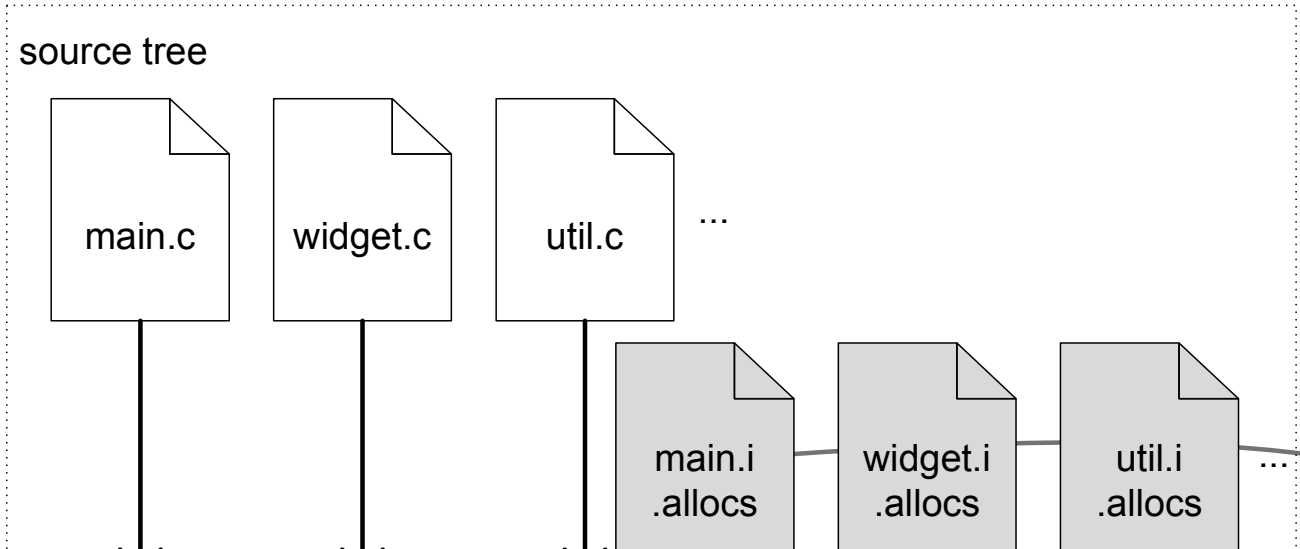
Dump *typed allocation sites* from compiler, for later pick-up



Polymorphism via multiply-indirected void

```
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];}
}
neighbor = (int **)calloc(NDIRS, sizeof(int *));
sort_eight_special ((void **) neighbor ); // <-- must allow!
```

- solution: tolerate casts from T** to void**...
- and check *writes through* void**
- ... *against the underlying object type* (here int *[])

Performance data: C-language SPEC CPU2006 benchmarks

bench	normal/s	crunch %	nopreload
bzip2	4.95	+6.8%	+1.4%
gcc	0.983	+160 %	– %
gobmk	14.6	+11 %	+2.0%
h264ref	10.1	+3.9%	+2.9%
hmmer	2.16	+8.3%	+3.7%
lbm	3.42	+9.6%	+1.7%
mcf	2.48	+12 %	(−0.5%)
milc	8.78	+38 %	+5.4%
sjeng	3.33	+1.5%	(−1.3%)
sphinx3	1.60	+13 %	+0.0%
perlbench			

Experience on "correct" code

benchmark	compile fixes	run-time false positives		
		instances	unique (of which...)	
			total	unhelpful
bzip2	0	48	3	3
gcc	1	3×10^5	14	3
gobmk	0	0	0	0
h264ref	2	27	2	0
hmmer	0	0	0	0
lbm	0	5×10^7	8	0
mcf	0	0	0	0
milc	0	0	0	0
sjeng	0	0	0	0
sphinx3	0	0	0	0

A “helpful” false positive?

```
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);}
```

Future work: shopping list for a *safe* implementation of C−ϵ

- check memcpy(), realloc(), etc..
- check syscalls (e.g. read())
- add a bounds checker (improve on SoftBound)
- add a GC (precise! improve on Boehm)
- check unions and varargs
- always initialize pointers
- check unsafe writes through char*
- safely address-takeable union members (!)

Good prospects for all of the above! (ask me)

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Plenty of existing tools do bounds checking

Memcheck (coarse), ASan (fine-ish), SoftBound (fine) …

- detect out-of-bounds pointer/array use
- first two also catch some temporal errors

Problems remaining:

- overhead at best 50–100% (ASan & SoftBound)
- problems mixing uninstrumented code (libraries)
- *false positives and negatives*
- abort on false positives

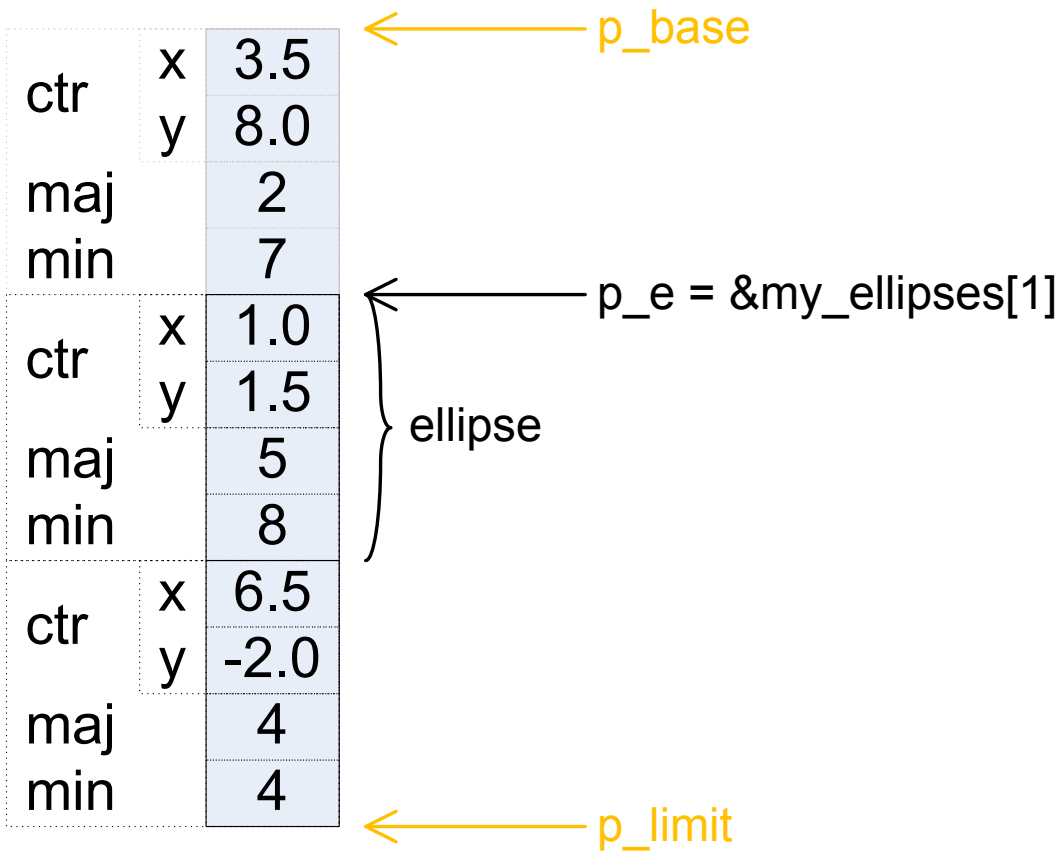
Difficult-to-check bounds errors and non-errors

```
typedef struct {int x[2]; char y[2];} blah;
blah z = { {0, 0}, "!" };

*(z.x + 2);              // error: subobject overflow
((int*) &z)[2];          // error: after bounds-narrowing cast

*((z.x + 42) - 42);      // non-error: via invalid (OOB) intermediate
((blah *) z.x)->y;       // non-error: after bounds-widening cast
*(int*)( intptr_t )z.x;  // non-error: via integer
* strfry (z.y);          // non-error: after uninstrumented code
```

Existing checkers using per-pointer metadata

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struct ellipse {
  struct point {
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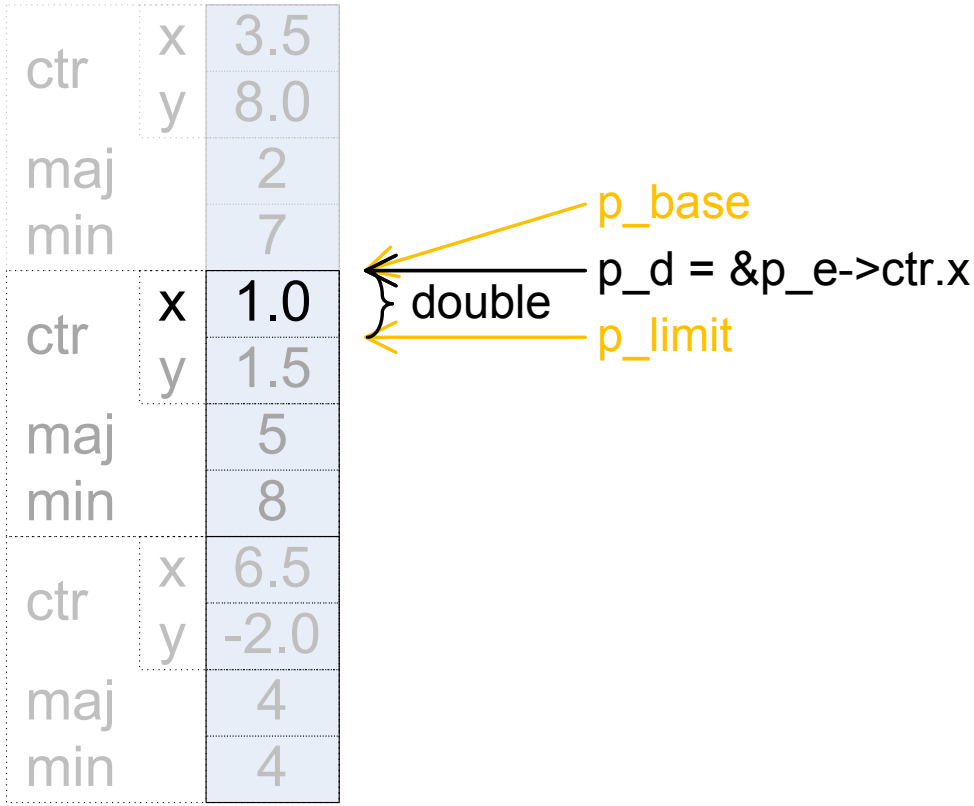


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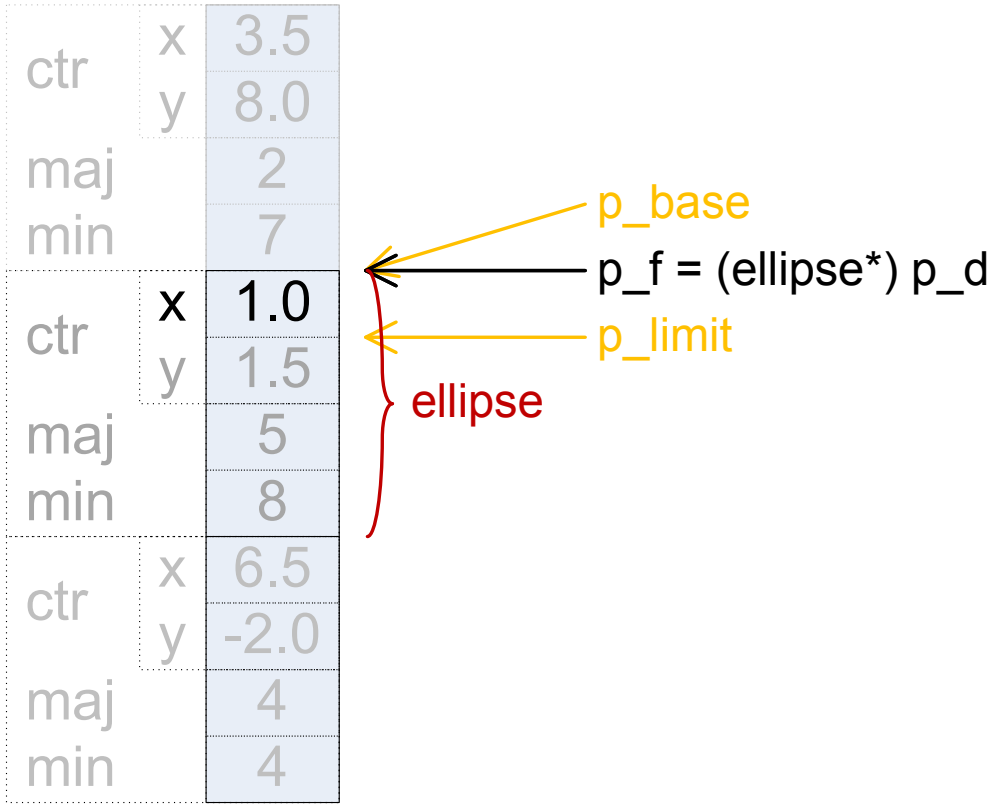
Without type information, pointer bounds lose precision

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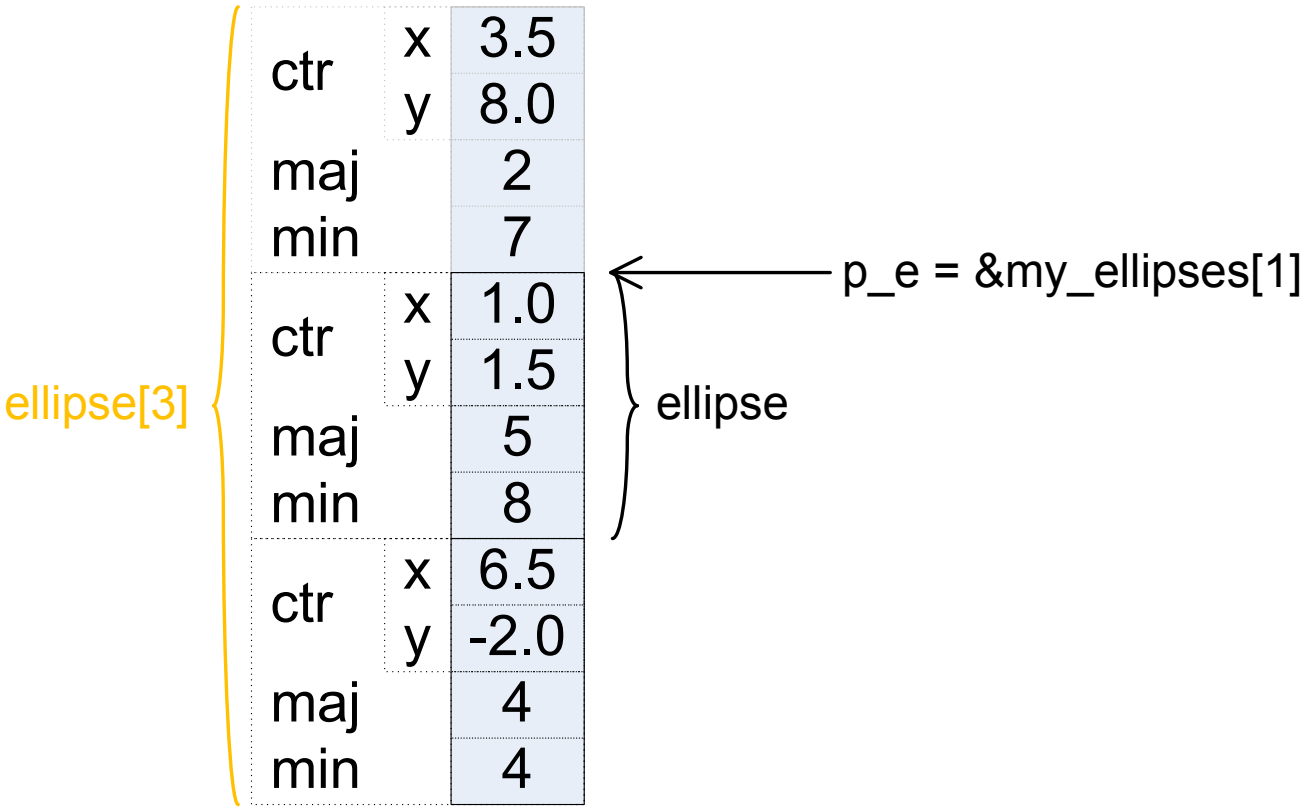
Given allocation type and pointer type, bounds are implicit

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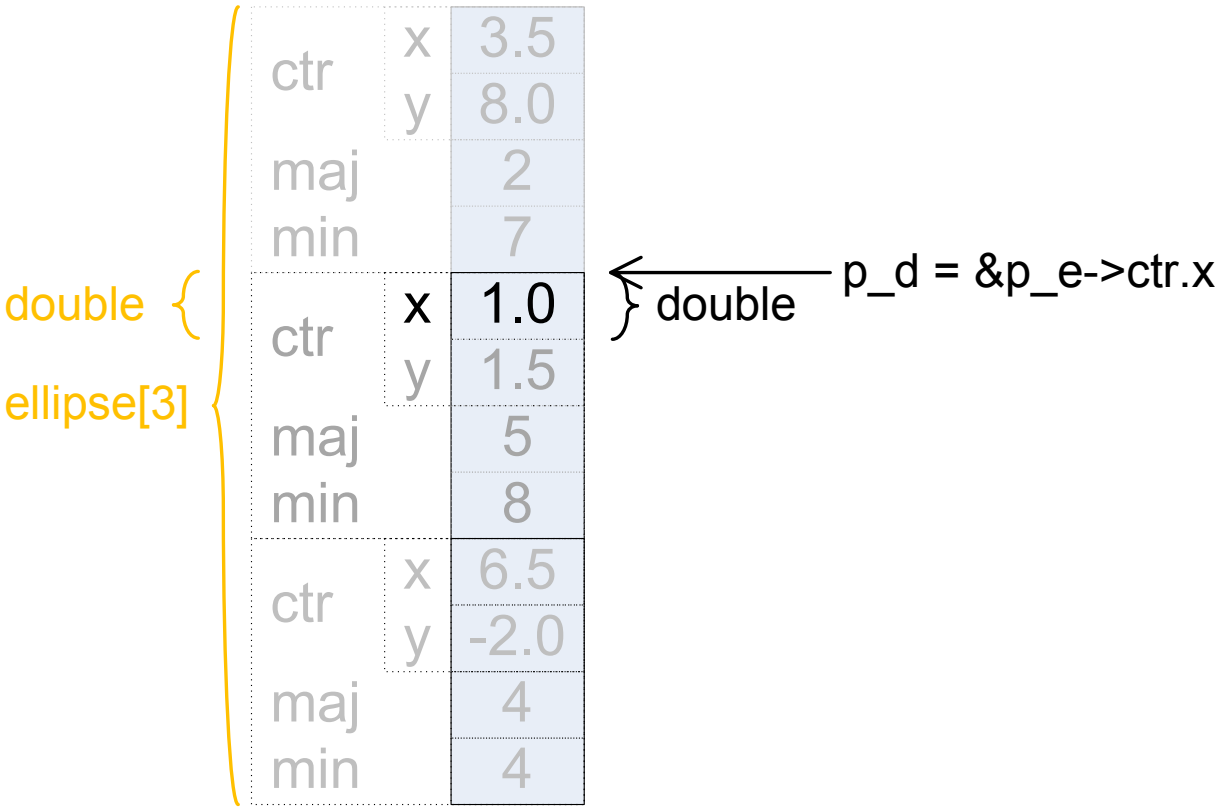


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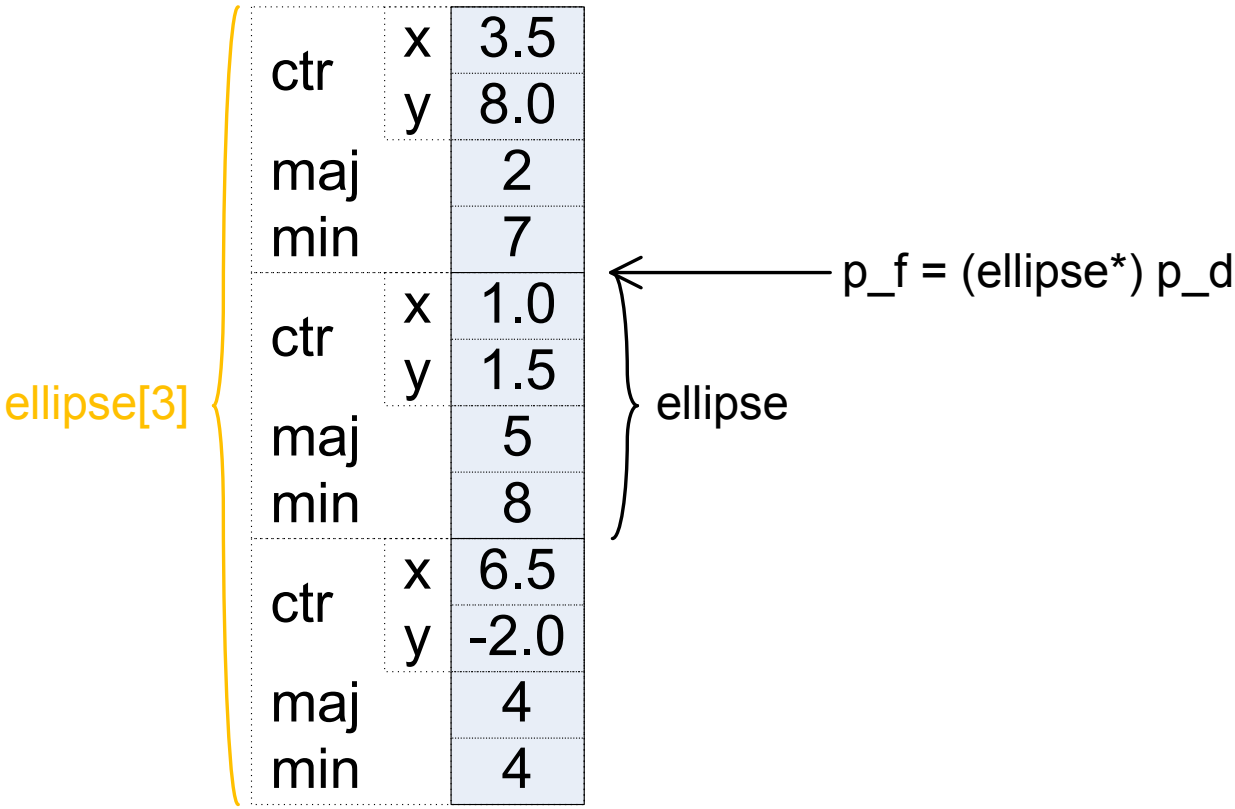


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The importance of being type-aware (when bounds-checking)

```
struct driver       { /* ... */ } *d = /* ... */;
struct i2c_driver { /* ... */ struct driver driver; /* ... */ };

#define container_of(ptr, type, member) \
 ((type *)( (char *)(ptr) - offsetof(type,member) ))

i2c_drv = container_of(d, struct i2c_driver, driver);
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SoftBound is oblivious to casts, even though they matter:

- bounds of d: just the smaller struct
- bounds of the char*: the whole allocation
- bounds of i2c_drv: the bigger struct

If only we knew the *type* of the storage!

Idea

Write a bounds-checker consuming per-allocation metadata

- avoid these false positives
- avoid libc wrappers, . . .
- robust to uninstrumented callers/callees
- performance?

Making it fast:

- cache bounds: make pointers “locally fat, globally thin”
- only check *derivation*, not *use*

Handling one-past pointers (diagram: Vladsinger, CC-BY-SA 3.0)

On x86-64, use noncanonical addresses as trap reps

No more deref checking

```
int ret = 0;
for (int i = 0; i < n; ++i)
{ struct list_node *p = malloc(sizeof (struct list_node ));
  p->next = head;
  head = p;
}
for (int i = 0; i < m; ++i)
{ unsigned out = 0;
  for (struct list_node *p = head; p; p = p->next)
  { out += p->x; }
  ret += out;
}
return ret ;
```

Status of the bounds checking

It “works”!

- still turning the handle…

Early indications

- array-based programs: SoftBound-like perf
  - mostly +50–100%
- linked structures: much faster!
  - as expected
- building my own SoftBound-alike to compare…

Conclusions

Run-time type info enables efficient and helpful checking

- source- and binary-compatible
- low overhead type checking
- precise & fast bounds checking
- good prospects for extension

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

Thanks for your attention. Questions?