Formal C semantics: CompCert and the C standard

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July 17, 2014 @ ITP, Vienna, Austria

Underspecification in C

- **Unspecified behavior**: two or more behaviors are allowed
  For example: order of evaluation in expressions

- **Implementation defined behavior**: like unspecified behavior, but the compiler has to document its choice
  For example: size and endianness of integers

- **Undefined behavior:** the standard imposes no requirements at all, the program is even allowed to crash
  For example: dereferencing a `NULL` or dangling pointer, signed integer overflow, . . .

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- **Unspecified behavior**: two or more behaviors are allowed
  For example: order of evaluation in expressions
  Non-determinism
- **Implementation defined behavior**: like unspecified behavior, but the compiler has to document its choice
  For example: size and endianness of integers
  Parametrization
- **Undefined behavior:** the standard imposes no requirements at all, the program is even allowed to crash
  For example: dereferencing a `NULL` or dangling pointer, signed integer overflow, . . .
  No semantics/crash state

Pros and cons of underspecification

Pros for optimizing compilers:

- More optimizations are possible
- High run-time efficiency
- Easy to support multiple architectures

Cons for programmers/formal methods people:

- Portability and maintenance problems
- Hard to formally reason about

Approaches to underspecification

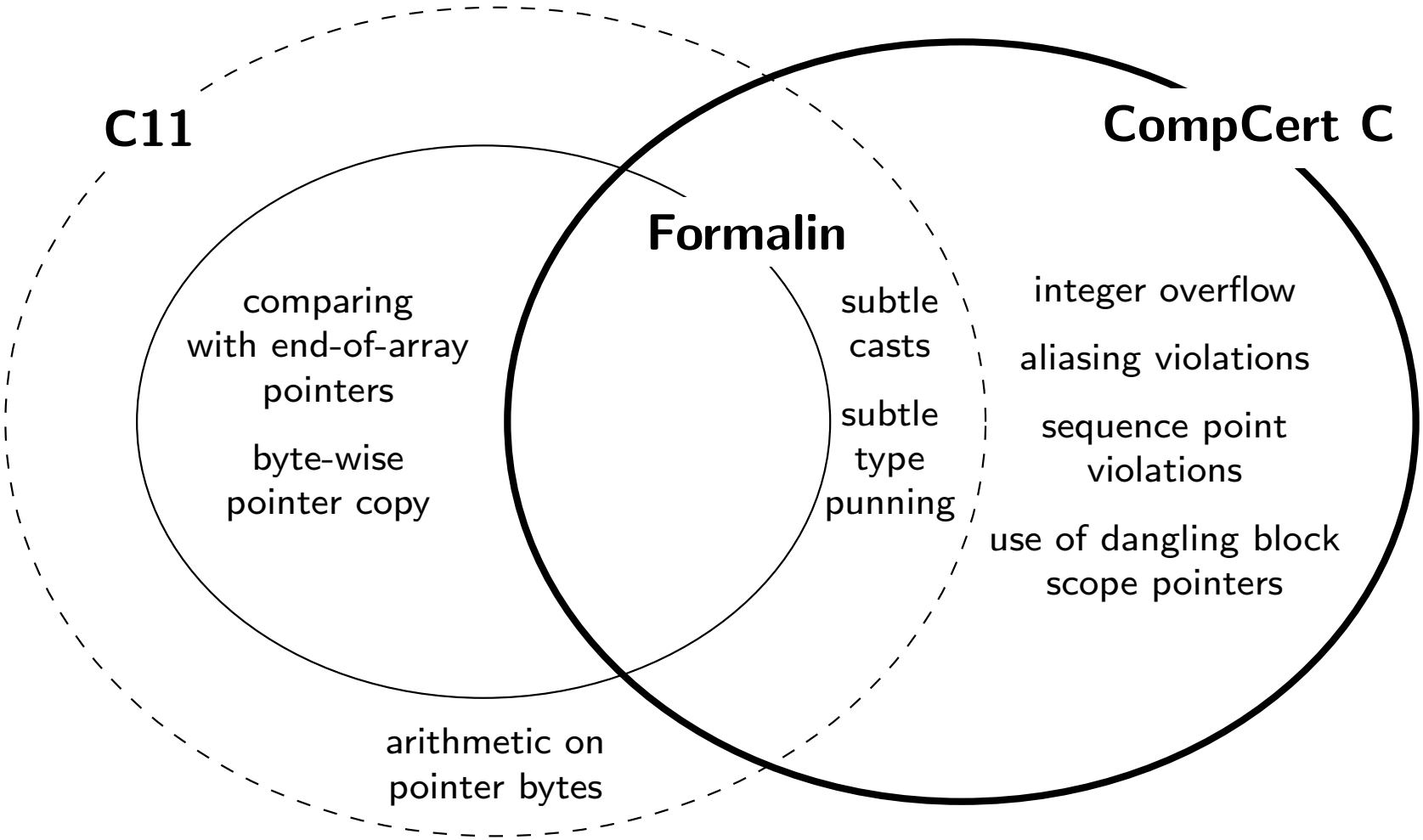
CompCert (Leroy *et al.*)

- Main goal: verified optimizing compiler in 
- Specific choices for unspecified/impl-defined behavior
  For example: 32-bits `ints`
- Describes some undefined behavior
  For example: dereferencing NULL, integer overflow defined
- Compiler correctness proof only for programs without undefined behavior

Formalin (Krebbers & Wiedijk)

- Main goal: compiler independent separation logic in 
- Describes some implementation-defined behavior
  For example: no legacy architectures with 1s' complement
- Aims to describe all unspecified and undefined behavior

Defined behaviors in C11, Formalin and CompCert C



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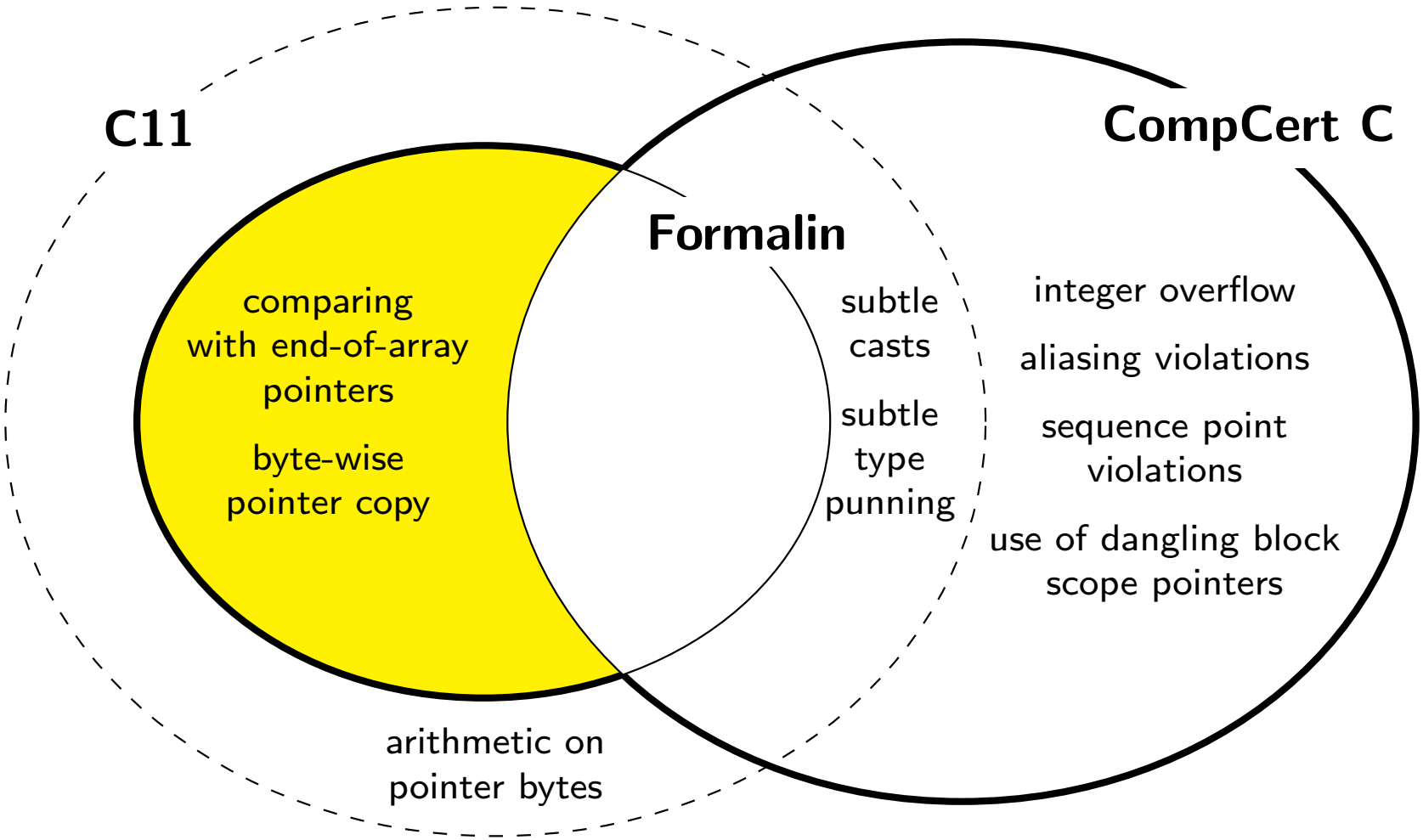

This talk: add  to **CompCert** so we get **Formalin** $\subseteq$ **CompCert**

Comparing with end-of-array pointers (problem)

Useful:

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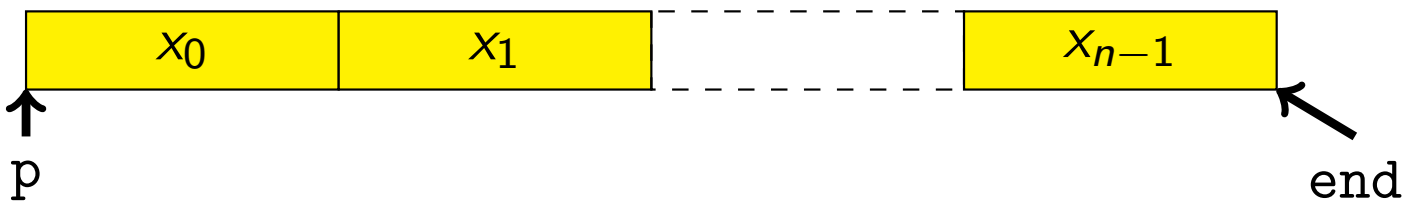

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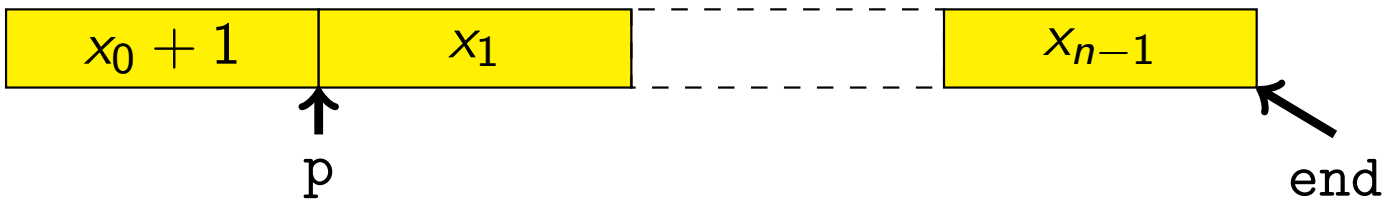

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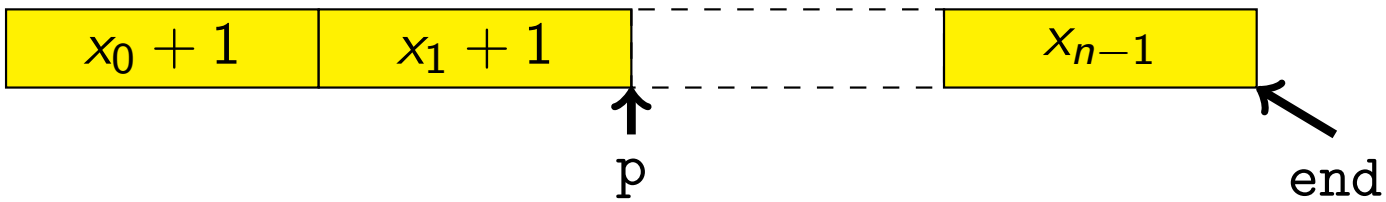

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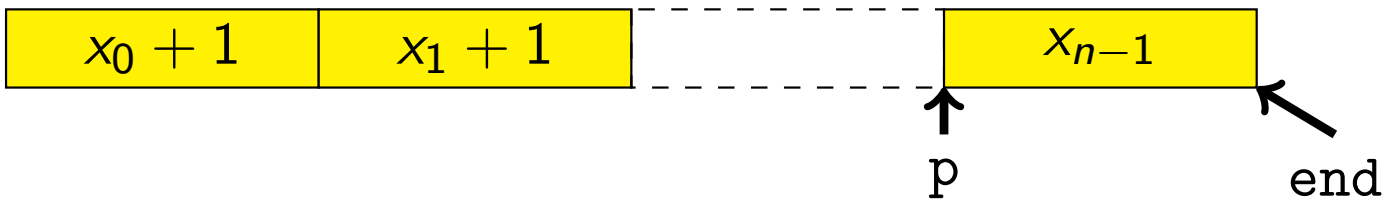

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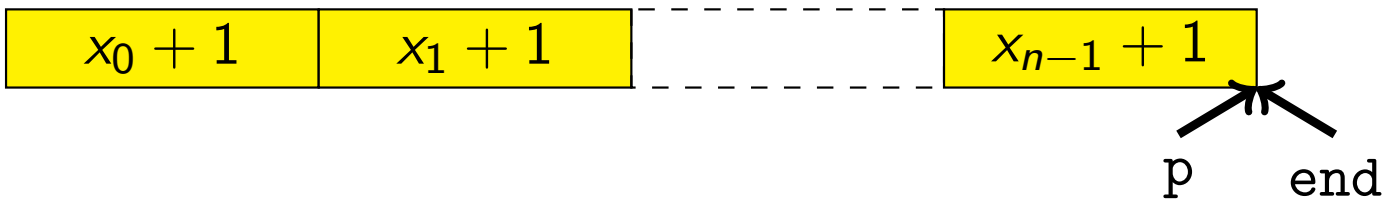

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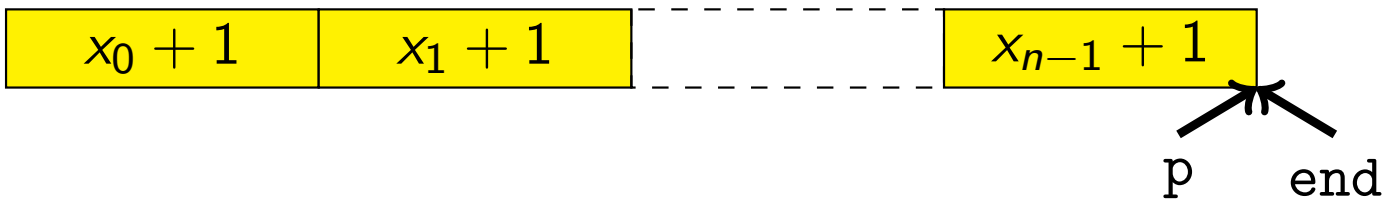

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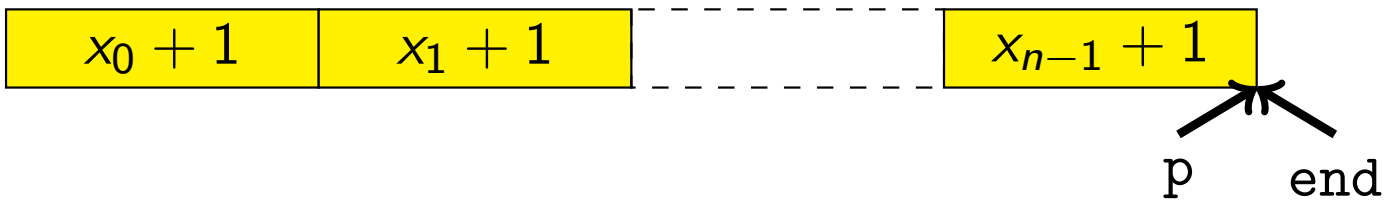

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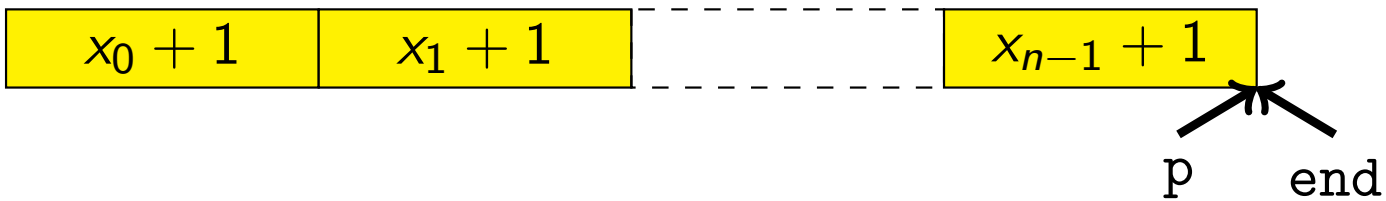

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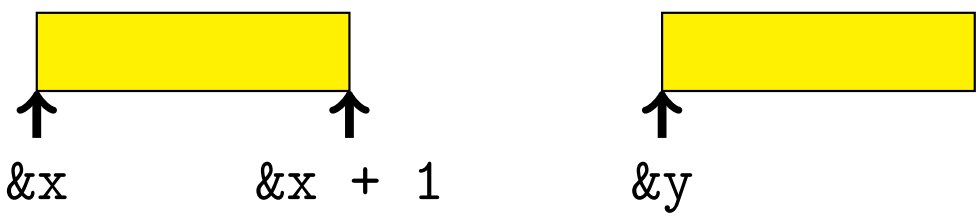

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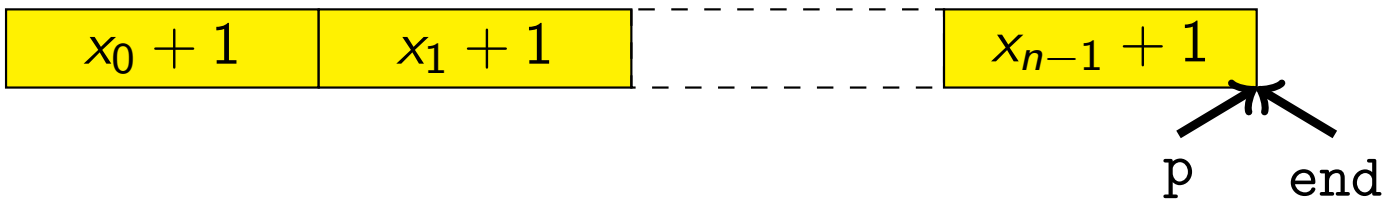

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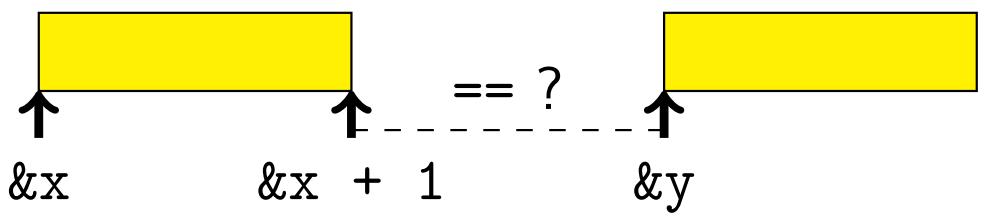

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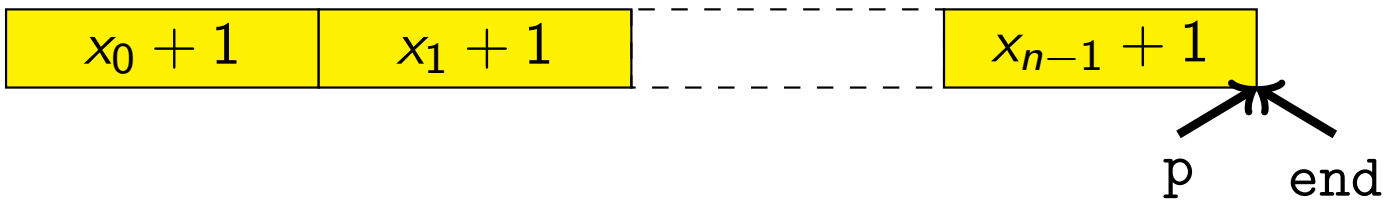

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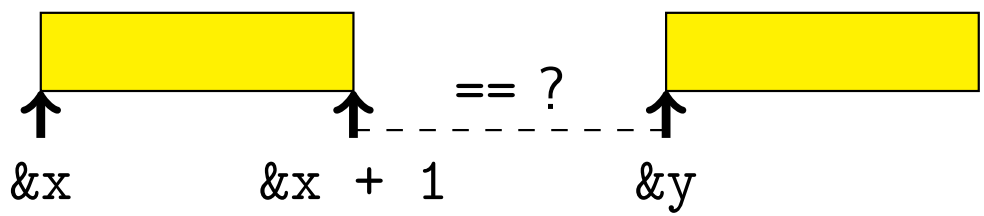

Both undefined behavior in CompCert (1.12 and before)

Comparing with end-of-array pointers (solution)

Solution: Comparison of pointers is defined if:

- Same block: both should within block bounds

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Stable under compilation and gives a semantics to common programming practice with end-of-array pointers

Byte-wise copying of objects (problem)

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struct { short x; short *r; } s1 = {10, &s.x}, s2;
unsigned char *p = &s1, *q = &s2;
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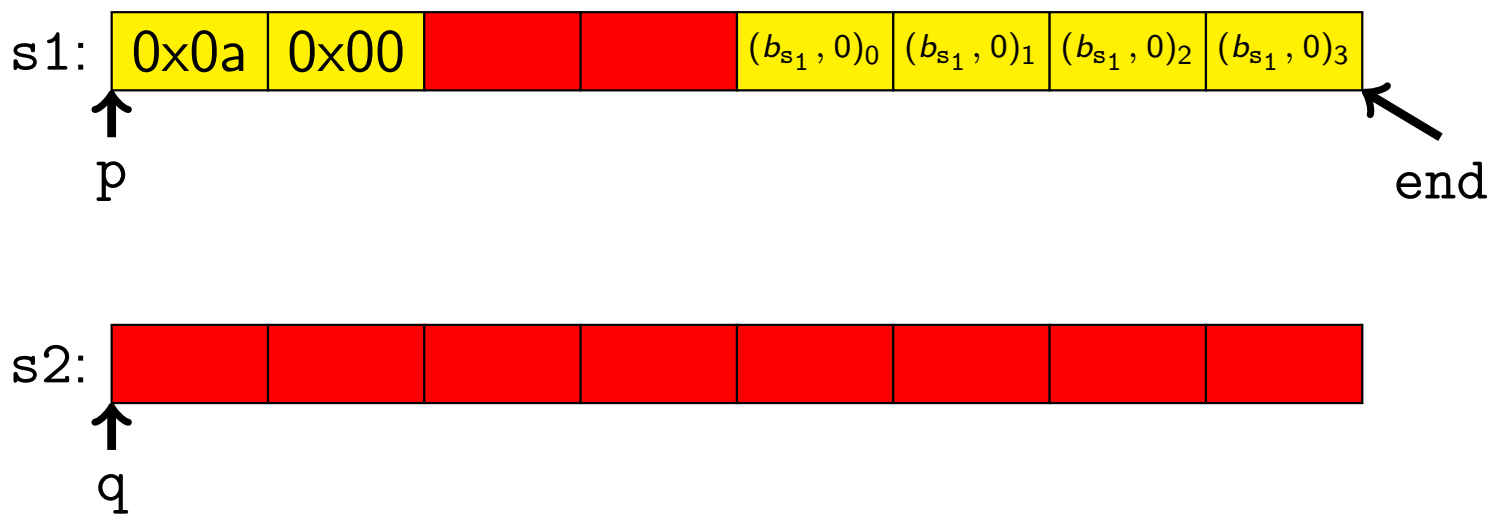

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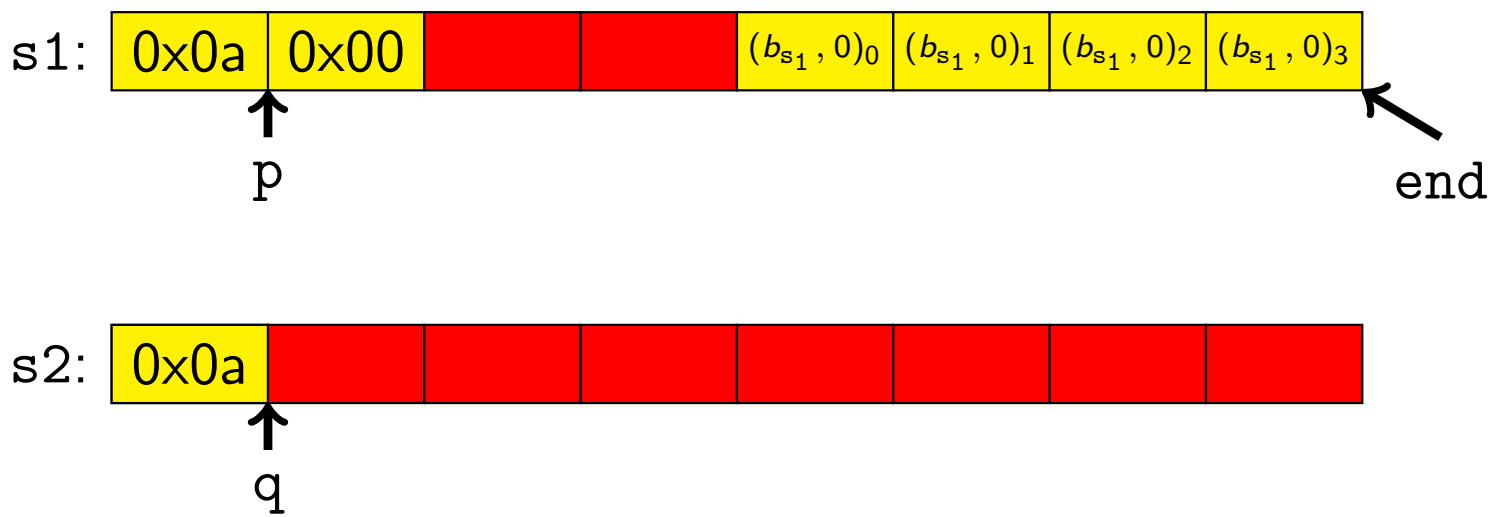

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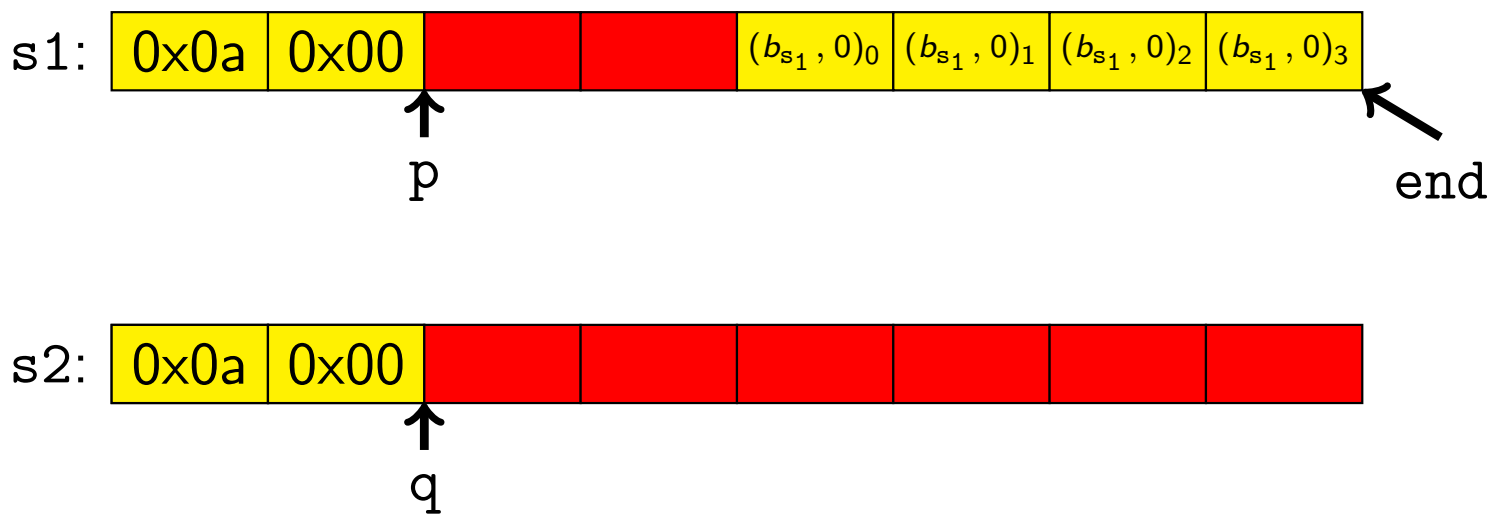

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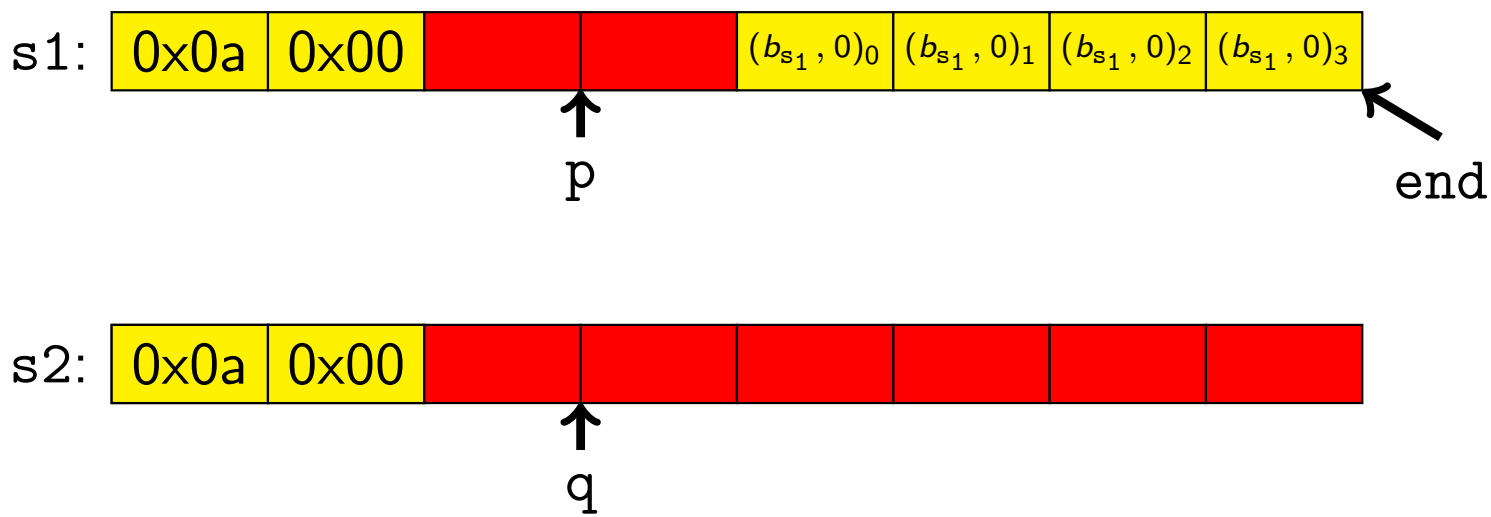

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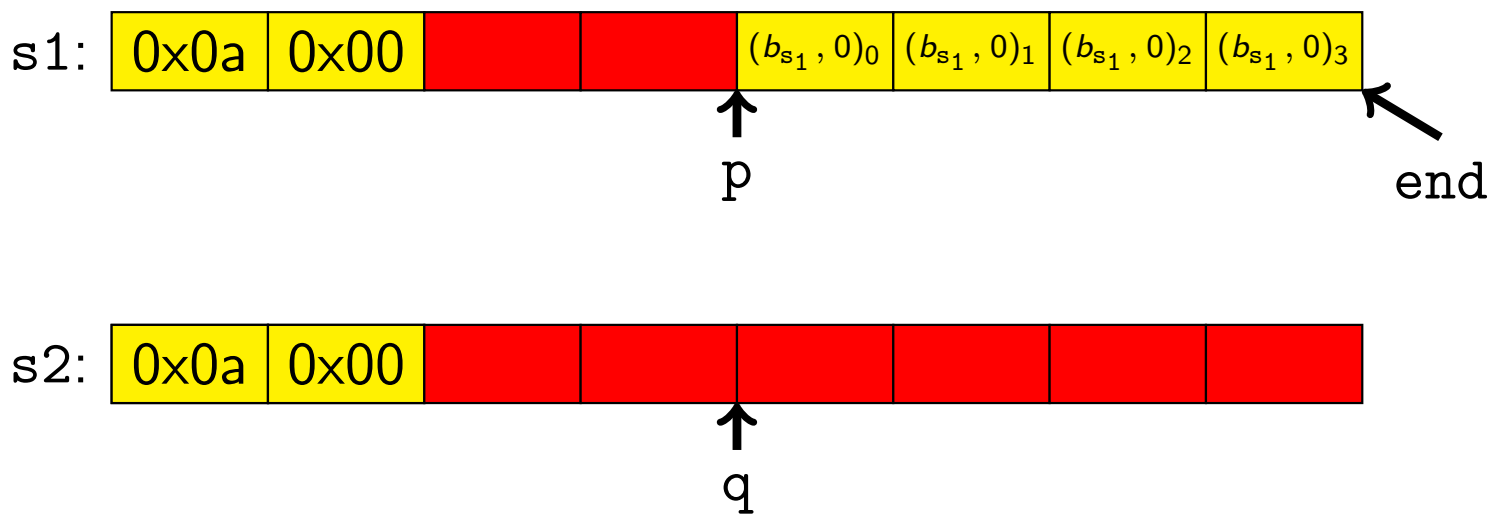

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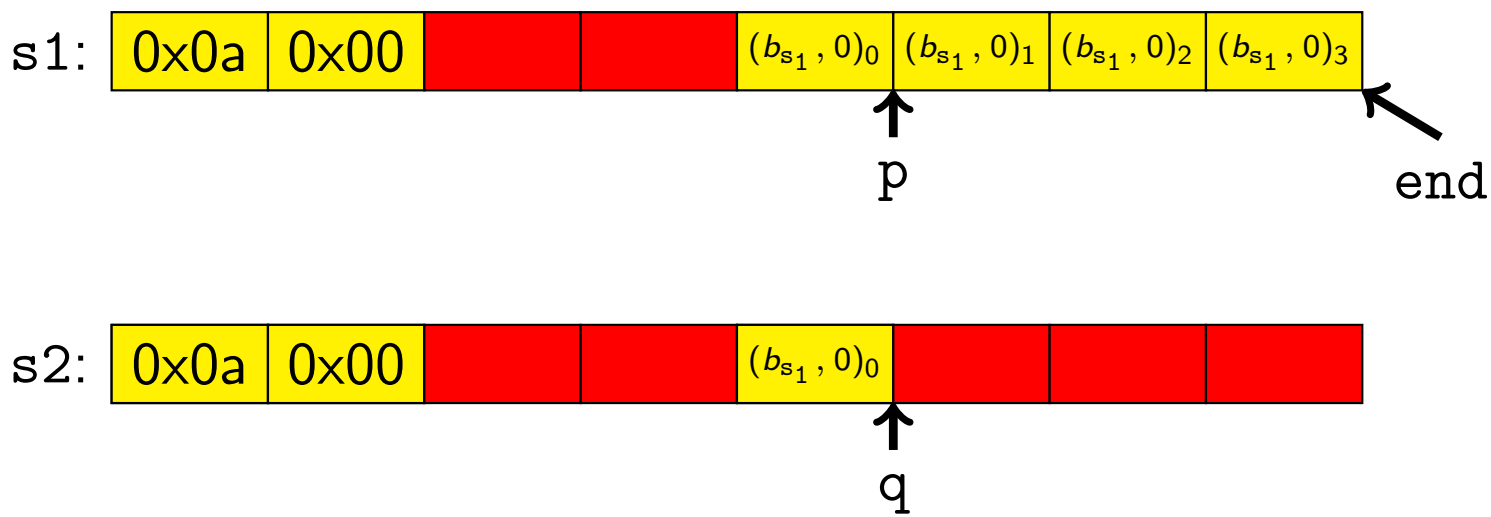

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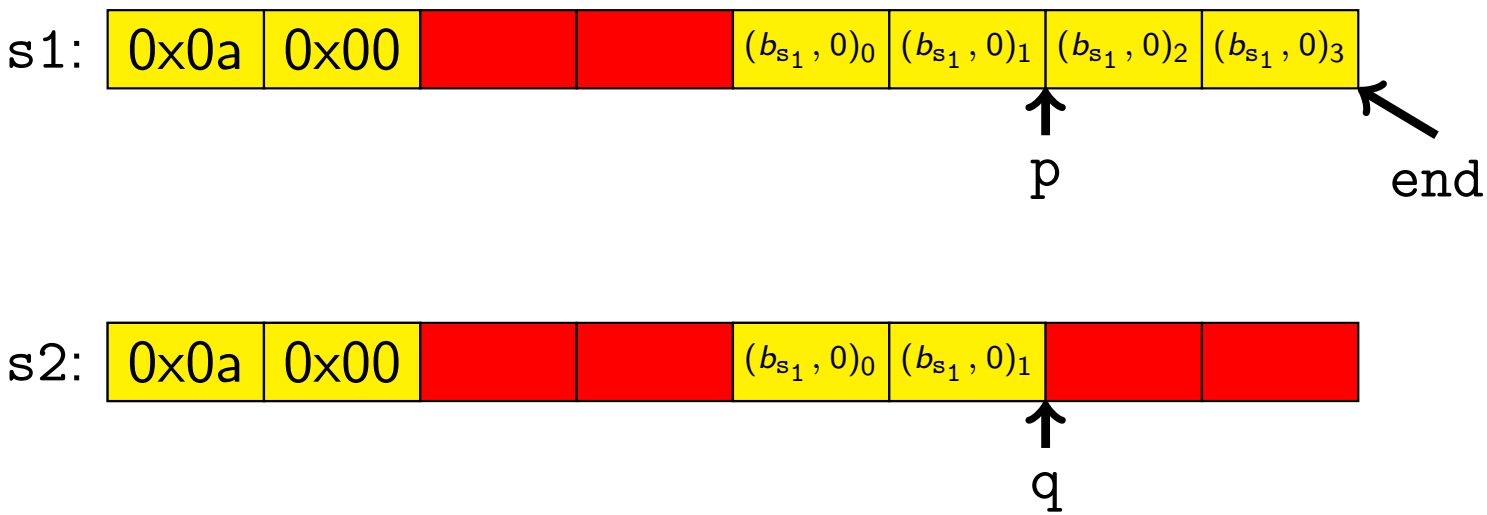

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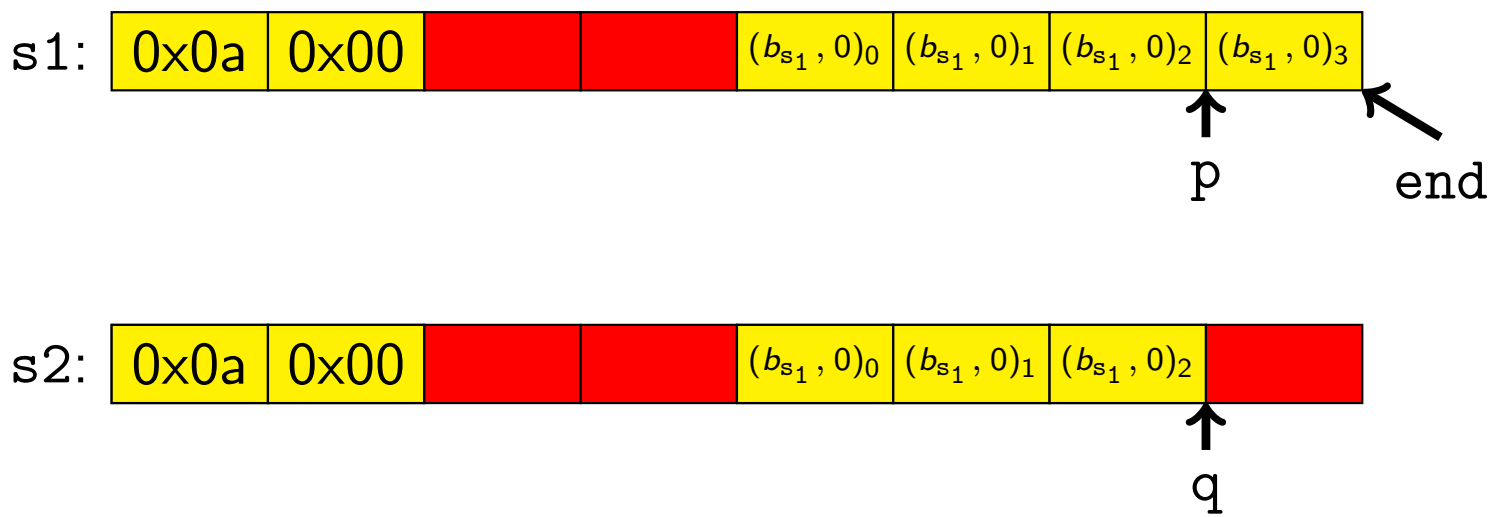

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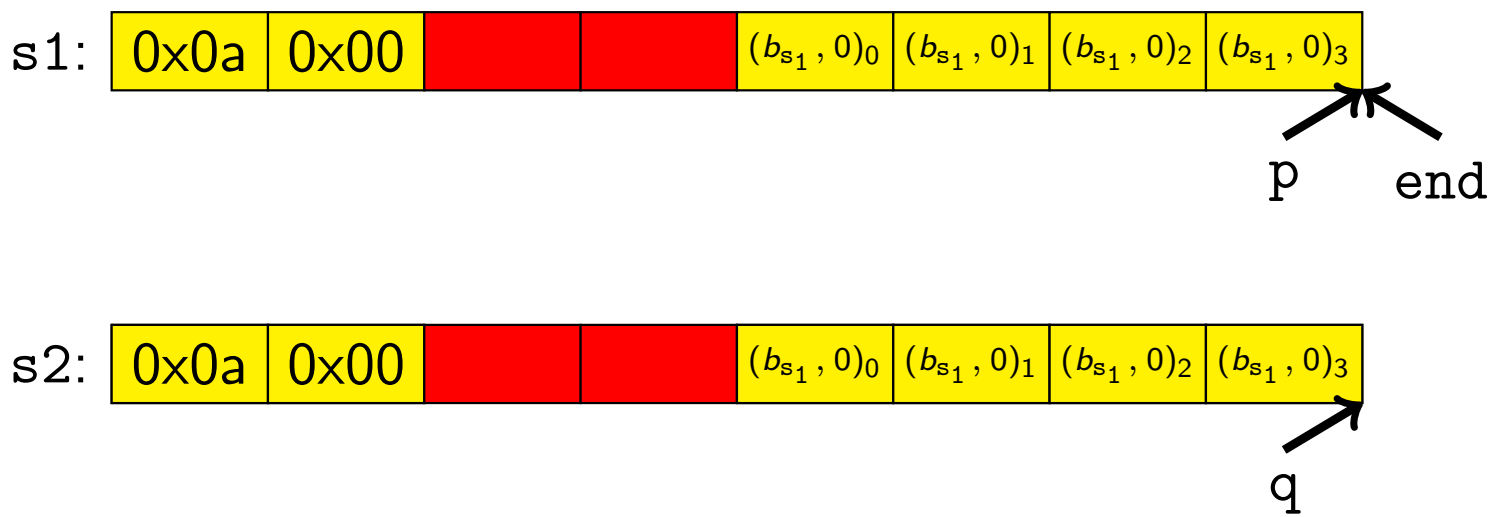

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Byte-wise copying of objects (solution)

Solution: extend values with *pointer fragment* values

```
Inductive val: Type :=
  | Vundef: val
  | Vint: int -> val
  | Vlong: int64 -> val
  | Vfloat: float -> val
  | Vptr: block -> int -> val
  | Vptrfrag: block -> int -> nat -> val.
```

Subtleties:

- Dealing with arithmetic on pointer fragments
- Dealing with implicit casts (at assignments)
- More values possible, need to extend static analysis

Conclusion and future work

- Semantics to useful behaviors that were previously undefined
  - Comparing with end-of-array pointers
  - Byte-wise pointer copy
- CompCert proofs adapted for these extensions
  - Small changes to the semantics
  - Involves proofs of many compilation passes
- Needed for cross validation of CompCert and Formalin
- Call-by-reference passing of struct values future work

Questions

Sources: `http://github.com/robbertkrebbers`