HARVARD
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CS153: Compilers
Lecture 6: Intermediate Representation and LLVM

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https://www.seas.harvard.edu/courses/cs153

Contains content from lecture notes by Steve Zdancewic and Greg Morrisett

Announcements

- Homework 1 grades returned
  - Style
  - Testing
- Homework 2: X86lite
  - Due Tuesday Sept 24
- Homework 3: LLVMlite
  - Will be released Tuesday Sept 24

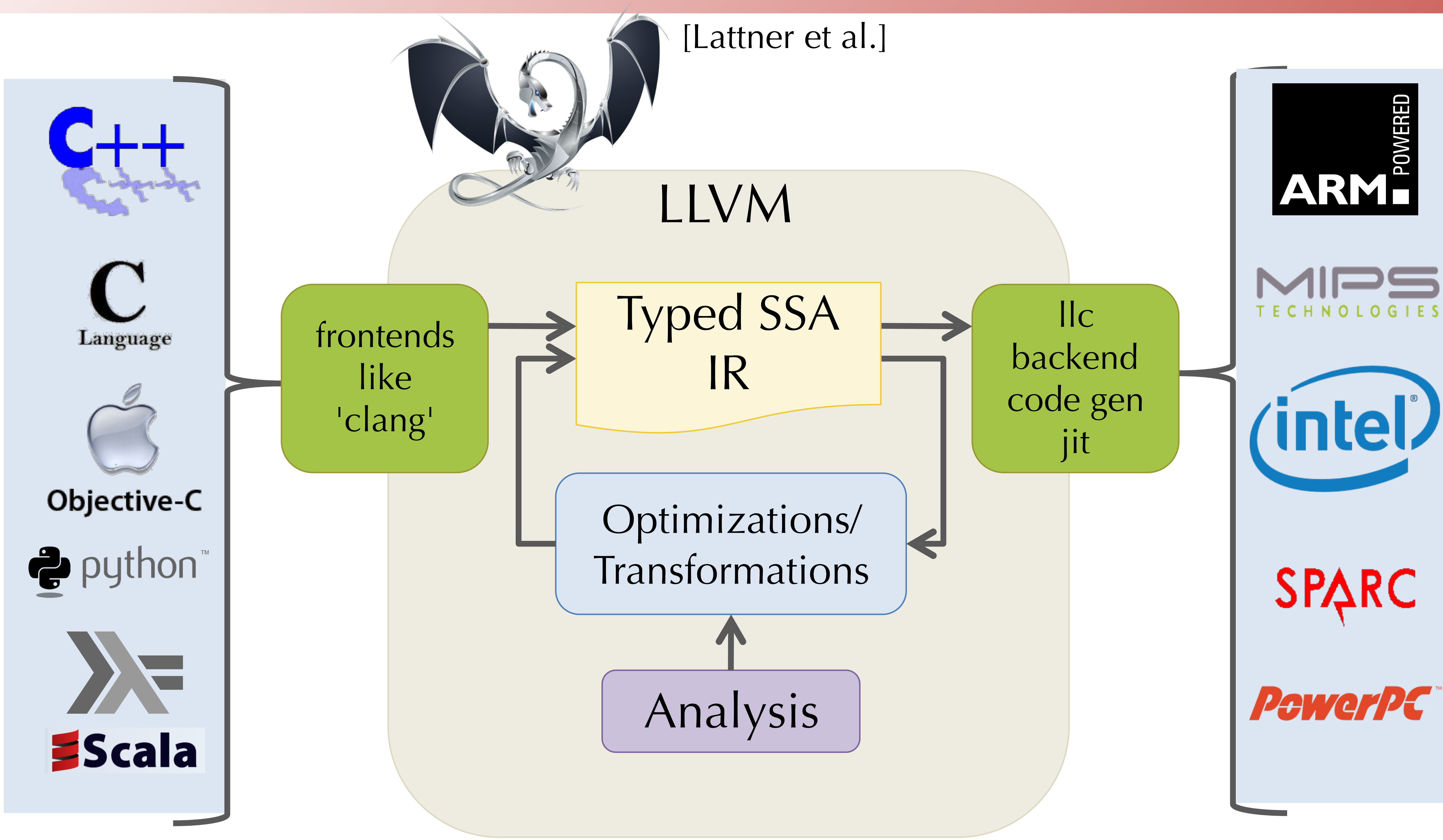
Today

- Continue Intermediate Representation
- Intro to LLVM

Low-Level Virtual Machine (LLVM)

- Open-Source Compiler Infrastructure
  - see llvm.org for full documentation
- Created by Chris Lattner (advised by Vikram Adve) at UIUC
  - LLVM: An infrastructure for Multi-stage Optimization, 2002
  - LLVM: A Compilation Framework for Lifelong Program Analysis and Transformation, 2004
- 2005: Adopted by Apple for XCode 3.1
- Front ends:
  - llvm-gcc (drop-in replacement for gcc)
  - Clang: C, objective C, C++ compiler supported by Apple
  - various languages: Swift, ADA, Scala, Haskell, …
- Back ends:
  - x86 / Arm / PowerPC / etc.
- Used in many academic/research projects

LLVM Compiler Infrastructure



Example LLVM Code

- LLVM offers a textual representation of its IR
  - files ending in .ll

factorial64.c

```
#include <stdio.h>
#include <stdint.h>

int64_t factorial(int64_t n) {
  int64_t acc = 1;
  while (n > 0) {
    acc = acc * n;
    n = n - 1;
  }
  return acc;
}
```

factorial-pretty.ll

```
define @factorial(%n) {
  %1 = alloca
  %acc = alloca
  store %n,  %1
  store 1,  %acc
  br label %start

start:
  %3 = load %1
  %4 = icmp sgt %3, 0
  br %4, label %then, label %else

then:
  %6 = load %acc
  %7 = load %1
  %8 = mul %6, %7
  store %8, %acc
  %9 = load %1
  %10 = sub %9, 1
  store %10, %1
  br label %start

else:
  %12 = load %acc
  ret %12
}
```

Real LLVM

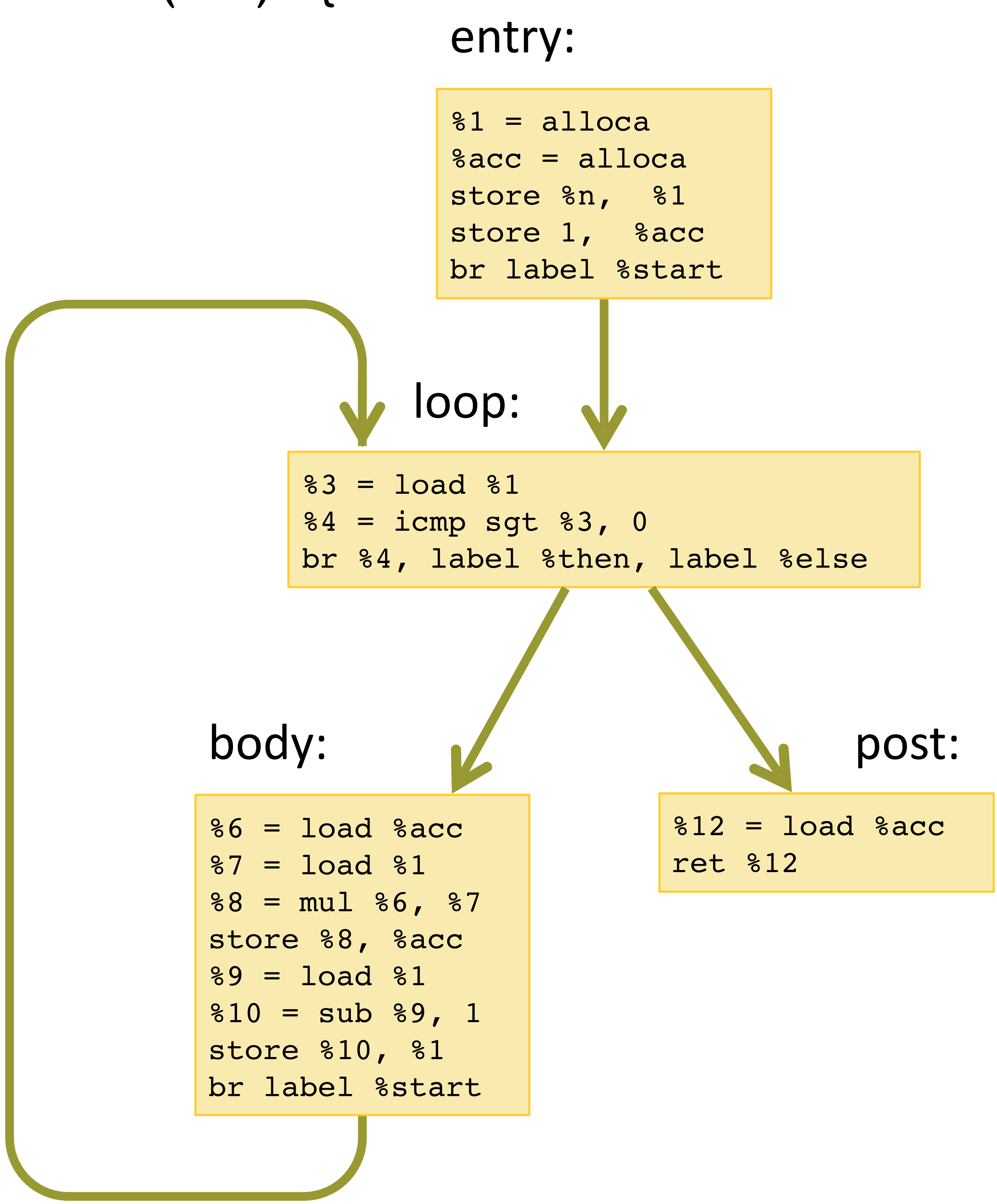
- Decorates values with type information
  - `i64`
  - `i64*`
  - `i1`
- Permits numeric identifiers
- Has alignment annotations
- Keeps track of entry edges for each block: `preds = %5, %0`

factorial.ll

```
; Function Attrs: nounwind ssp
define i64 @factorial(i64 %n) #0 {
  %1 = alloca i64, align 8
  %acc = alloca i64, align 8
  store i64 %n, i64* %1, align 8
  store i64 1, i64* %acc, align 8
  br label %2

; <label>:2                                       ; preds = %5, %0
  %3 = load i64* %1, align 8
  %4 = icmp sgt i64 %3, 0
  br i1 %4, label %5, label %11

; <label>:5                                       ; preds = %2
  %6 = load i64* %acc, align 8
  %7 = load i64* %1, align 8
  %8 = mul nsw i64 %6, %7
  store i64 %8, i64* %acc, align 8
  %9 = load i64* %1, align 8
  %10 = sub nsw i64 %9, 1
  store i64 %10, i64* %1, align 8
  br label %2

; <label>:11                                      ; preds = %2
  %12 = load i64* %acc, align 8
  ret i64 %12
}
```

Example Control-flow Graph

```
define @factorial(%n) {
```




```
}
```

LL Basic Blocks and Control-Flow Graphs

- LLVM enforces (some of) the basic block invariants syntactically.
- Representation in OCaml:

```
type block = {
    insns : (uid * insn) list;
    term  : (uid * terminator)
}
```

- A **control flow graph** is represented as a list of labeled basic blocks with these invariants:
  - No two blocks have the same label
  - All terminators mention only labels that are defined among the set of basic blocks
  - There is a distinguished, unlabeled, entry block:

```
type cfg = block * (lbl * block) list
```

LL Storage Model: Locals

- Several kinds of storage:
  - Local variables (or temporaries): `%uid`
  - Global declarations (e.g. for string constants): `@gid`
  - Abstract locations: references to (stack-allocated) storage created by the `alloca` instruction
  - Heap-allocated structures created by external calls (e.g. to `malloc`)

- Local variables:
  - Defined by the instructions of the form %uid = …
  - Must satisfy the single static assignment invariant
    - Each `%uid` appears on the left-hand side of an assignment only once in the entire control flow graph.
  - The value of a `%uid` remains unchanged throughout its lifetime
  - Analogous to "`let %uid = e in …`" in OCaml
- Intended to be an abstract version of machine registers.
- We'll see later how to extend SSA to allow richer use of local variables
  - **phi nodes**

LL Storage Model: `alloca`

- The `alloca` instruction allocates stack space and returns a reference to it.
  - The returned reference is stored in local:

    ```
    %ptr = alloca typ
    ```
  - The amount of space allocated is determined by the type

- The contents of the slot are accessed via the load and store instructions:

```
%acc = alloca i64                ; allocate a storage slot
store i64 341, i64* %acc         ; store the integer value 341
%x = load i64, i64* %acc         ; load the value 341 into %x
```

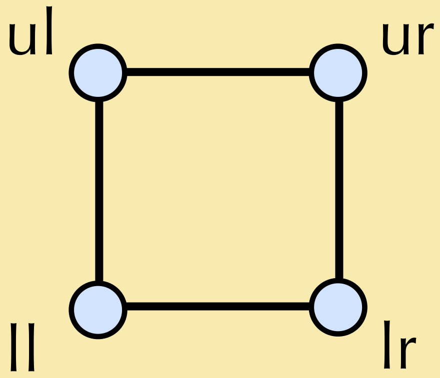
- Gives an abstract version of stack slots

Structured Data

Compiling Structured Data

- Consider C-style structures like those below.
- How do we represent `Point` and `Rect` values?

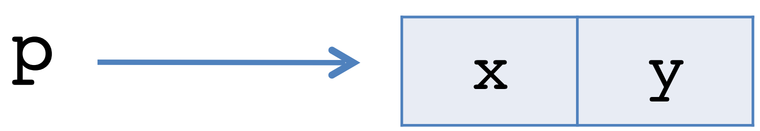
```
struct Point { int x; int y; };

struct Rect  { struct Point ll, lr, ul, ur };

struct Rect mk_square(struct Point ll, int len) {
  struct Rect square;
  square.ll = square.lr = square.ul = square.ur = ll;
  square.lr.x += len;
  square.ur.x += len;
  square.ur.y += len;
  square.ul.y += len;
  return square;
}
```



Representing Structs

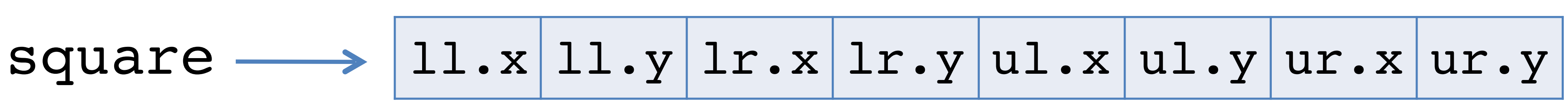
```
struct Point { int x; int y; };
```

- Store the data using two contiguous words of memory.
- Represent a `Point` value `p` as the address of the first word.




```
struct Rect  { struct Point ll, lr, ul, ur };
```

- Store the data using 8 contiguous words of memory.



- Compiler needs to know the **size** of the struct at compile time to allocate the needed storage space.
- Compiler needs to know the **shape** of the struct at compile time to index into the structure.

Assembly-level Member Access

square →

ll.x	ll.y	lr.x	lr.y	ul.x	ul.y	ur.x	ur.y

```
struct Point { int x; int y; };

struct Rect  { struct Point ll, lr, ul, ur };
```

- Consider: ⟦`square.ul.y`⟧ = (x86.insns, x86.operand)

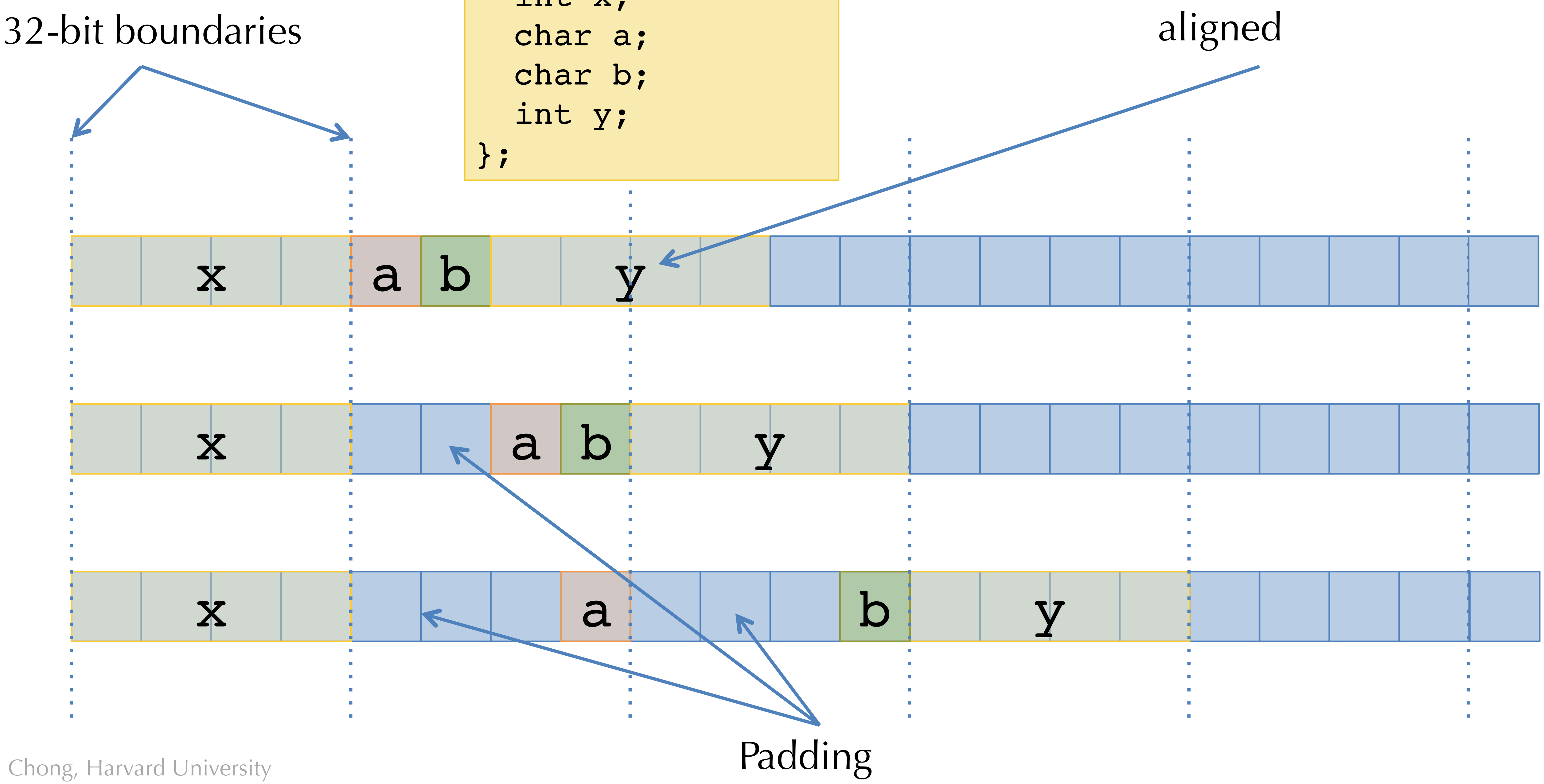
- Assume that `%rcx` holds the base address of `square`
- Calculate the offset relative to the base pointer of the data:
  - ul = sizeof(`struct Point`) + sizeof(`struct Point`)
  - y = sizeof(int)

- So: ⟦`square.ul.y`⟧ = (`Movq 20(%rcx) ans, ans`)

Padding & Alignment

- How to lay out non-homogeneous structured data?

```
struct Example {
  int x;
  char a;
  char b;
  int y;
};
```



Copy-in/Copy-out

- When we do an assignment in C as in:

```
struct Rect mk_square(struct Point ll, int elen) {
  struct Square res;
  res.lr = ll;
  ...
```

  we copy all elements from source and put in the target.

- Same as doing word-level operations:

```
struct Rect mk_square(struct Point ll, int elen) {
  struct Square res;
  res.lr.x = ll.x;
  res.lr.y = ll.x;
  ...
```

- For really large copies, the compiler uses something like **`memcpy`** (which is implemented using a loop in assembly).

C Procedure Calls

- Similarly, when we call a procedure, we copy arguments in, and copy results out
  - Caller sets aside extra space in its frame to store results that are bigger than will fit in `%rax`
  - We do the same with scalar values such as integers or doubles.
- Sometimes, this is termed "call-by-value".
  - This is bad terminology
  - Copy-in/copy-out is more accurate
- Benefit: locality
- Problem: expensive for large records…
- In C: can opt to pass pointers to structs: "call-by-reference"
  - Languages like Java and OCaml always pass non-word-sized objects by reference.

Call-by-Reference:

```
void mkSquare(struct Point *ll, int elen,
              struct Rect *res) {
  res->lr = res->ul = res->ur = res->ll = *ll;
  res->lr.x += elen;
  res->ur.x += elen;
  res->ur.y += elen;
  res->ul.y += elen;
}

void foo() {
  struct Point origin = {0,0};
  struct Square unit_sq;
  mkSquare(&origin, 1, &unit_sq);
}
```

- The caller passes in the address of the point and the address of the result (1 word each).

Stack Pointers Can Escape

- Note that returning references to stack-allocated data can cause problems…

```
int* bad() {
  int x = 341;
  int *ptr = &x;
  return ptr;
}
```

  - See `unsafestack.c`
- For data that persists across a function call, we need to allocate storage in the heap…
  - in C, use the `malloc` library