CPSC 213

Introduction to Computer Systems

Unit 1f

Dynamic Control Flow
Polymorphism and Switch Statements

Readings for Next Two to Three Lectures

- Text
  - Switch Statements, Understanding Pointers
    - 2nd ed: 3.6.7, 3.10
    - 1st ed: 3.6.6, 3.11

Polymorphism

Back to Procedure Calls

- Static Method Invocations and Procedure Calls
  - target method/procedure address is know statically
- in Java
  - *static* methods are class methods
    - invoked by naming the class, not an object

```
public class A {
  static void ping () {}
}

public class Foo {
  static void foo () {
    A.ping ();
  }
}
```

- in C
  - specify procedure name

```
void ping () {}

void foo () {
  ping ();
}
```

Polymorphism

- Invoking a method on an object in Java
  - variable that stores the object has a static type
  - object reference is dynamic and so is its type
    - object's type must implement the type of the referring variable
    - but object's type my override methods of this base type
- Polymorphic Dispatch
  - target method address depends on the type of the referenced object
  - one call site can invoke different methods at different times

```
class A {
  void ping () {}
  void pong () {}
}
```

```
class B extends A {
  void ping () {}
  void wiff () {}
}
```

```
static void foo (A a) {
  a.ping ();
  a.pong ();
}

static void bar () {
  foo (new A());
  foo (new B());
}
```

Which ping gets called?

Polymorphic Dispatch

- Method address is determined dynamically
  - compiler can not hardcode target address in procedure call
  - instead, compiler generates code to lookup procedure address at runtime
  - address is stored in memory in the object's class *jump table*
- Class Jump table
  - every class is represented by class object
  - the class object stores the class's jump table
  - the jump table stores the address of every method implemented by the class
  - objects store a pointer to their class object
- Static and dynamic of method invocation
  - address of jump table is determined dynamically
  - method's offset into jump table is determined statically

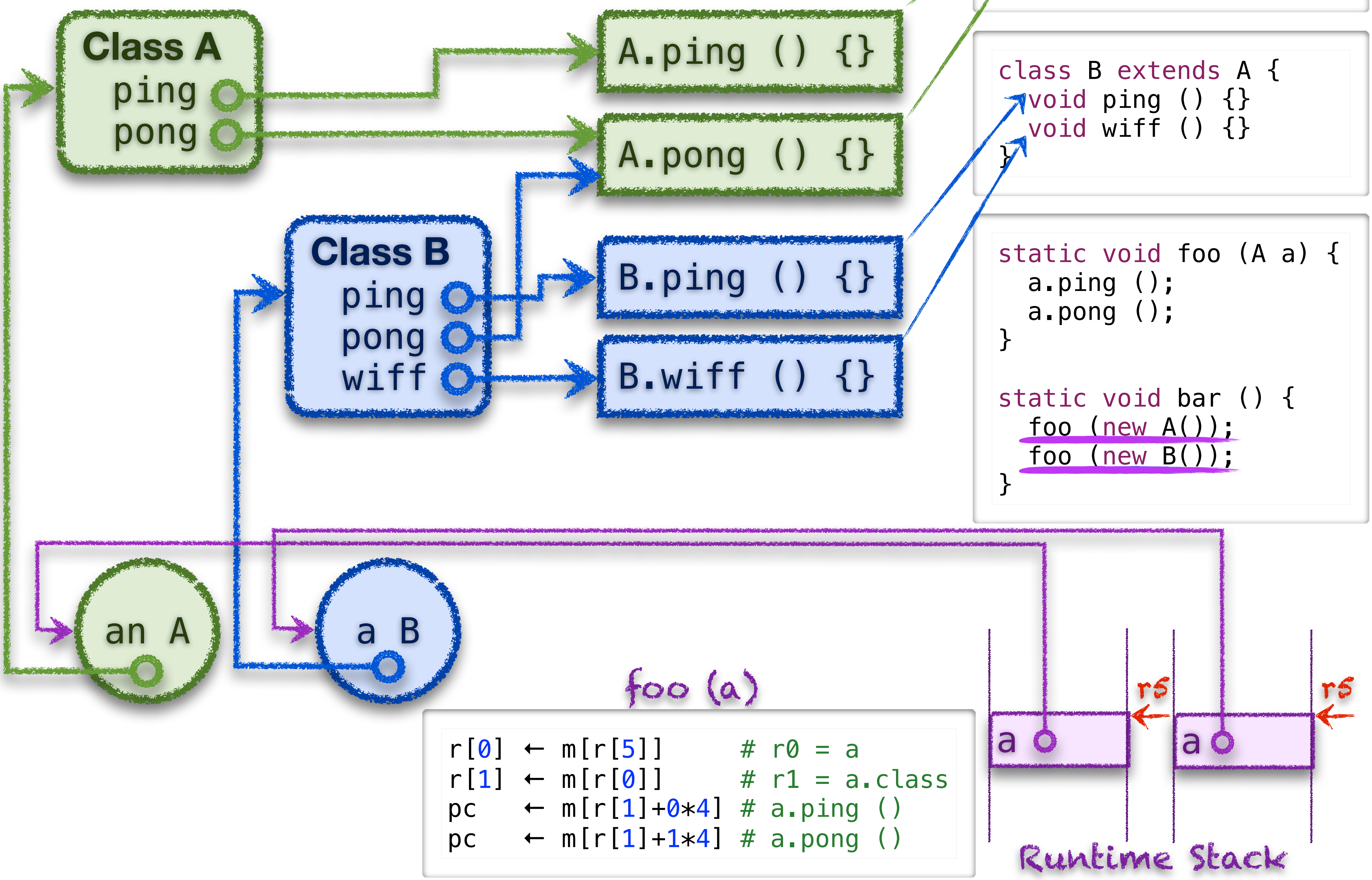
Example of Java Dispatch

```
class A {
  void ping () {}
  void pong () {}
}
```

```
class B extends A {
  void ping () {}
  void wiff () {}
}
```

```
static void foo (A a) {
  a.ping ();
  a.pong ();
}

static void bar () {
  foo (new A());
  foo (new B());
}
```




```
r[0] ← m[r[5]]       # r0 = a
r[1] ← m[r[0]]       # r1 = a.class
pc   ← m[r[1]+0*4]   # a.ping ()
pc   ← m[r[1]+1*4]   # a.pong ()
```

Dynamic Jumps in C

- Function pointer
  - a variable that stores a pointer to a procedure
  - declared
    - <return-type> (*<variable-name>)(<formal-argument-list>);
  - used to make dynamic call
    - <variable-name> (<actual-argument-list>);
- Example

```
void ping () {}
```

```
void foo () {
  void (*aFunc) ();

  aFunc = ping;
  aFunc (); calls ping
}
```

Simplified Polymorphism in C (SA-dynamic-call.c)

- Use a struct to store jump table
  - drawing on previous example of A ...

Declaration of A's jump table and code

```
struct A {
  void (*ping) ();
  void (*pong) ();
};

void A_ping () { printf ("A_ping\n"); }
void A_pong () { printf ("A_pong\n"); }
```

Create an instance of A's jump table

```
struct A* new_A () {
  struct A* a = (struct A*) malloc (sizeof (struct A));
  a->ping = A_ping;
  a->pong = A_pong;
  return a;
}
```

- and B ...

Declaration of B's jump table and code

```
struct B {
  void (*ping)();
  void (*pong)();
  void (*wiff)();
};

void B_ping () { printf ("B_ping\n"); }
void B_wiff () { printf ("B_wiff\n"); }
```

Create an instance of B's jump table

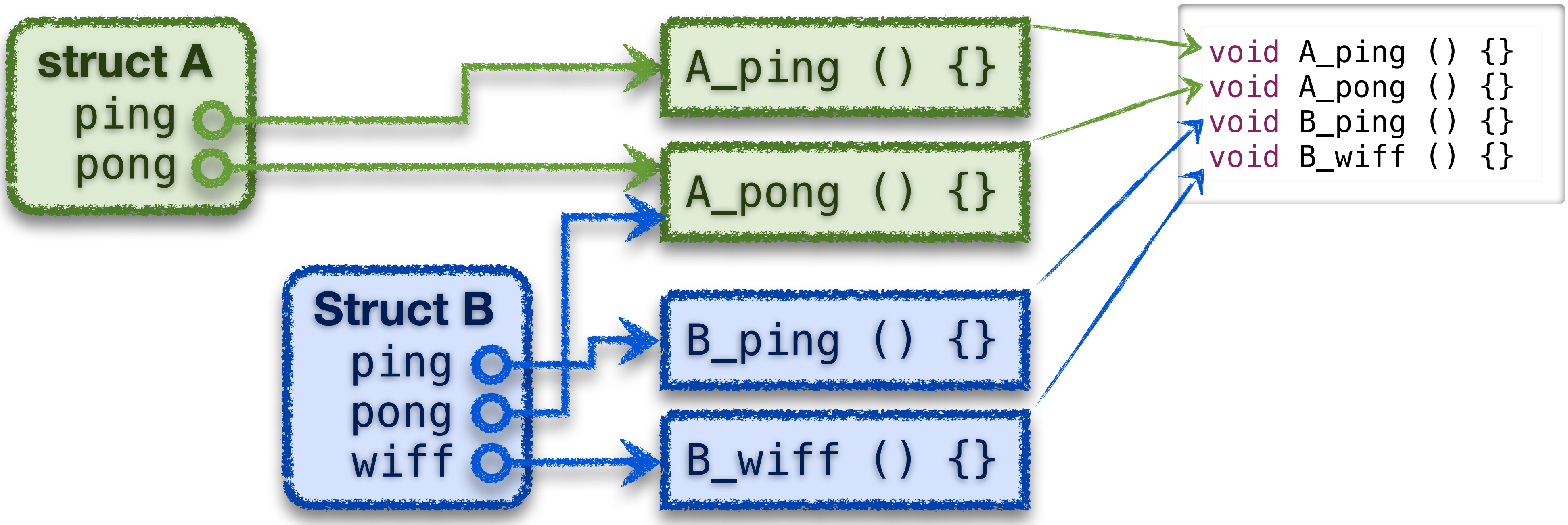
```
struct B* new_B () {
  struct B* b = (struct B*) malloc (sizeof (struct B));
  b->ping = B_ping;
  b->pong = A_pong;
  b->wiff = B_wiff;
  return b;
}
```

- invoking ping and pong on an A and a B ...

```
void foo (struct A* a) {
  a->ping ();
  a->pong ();
}

void bar () {
  foo (new_A ());
  foo ((struct A*) new_B ());
}
```

Dispatch Diagram for C (data layout)



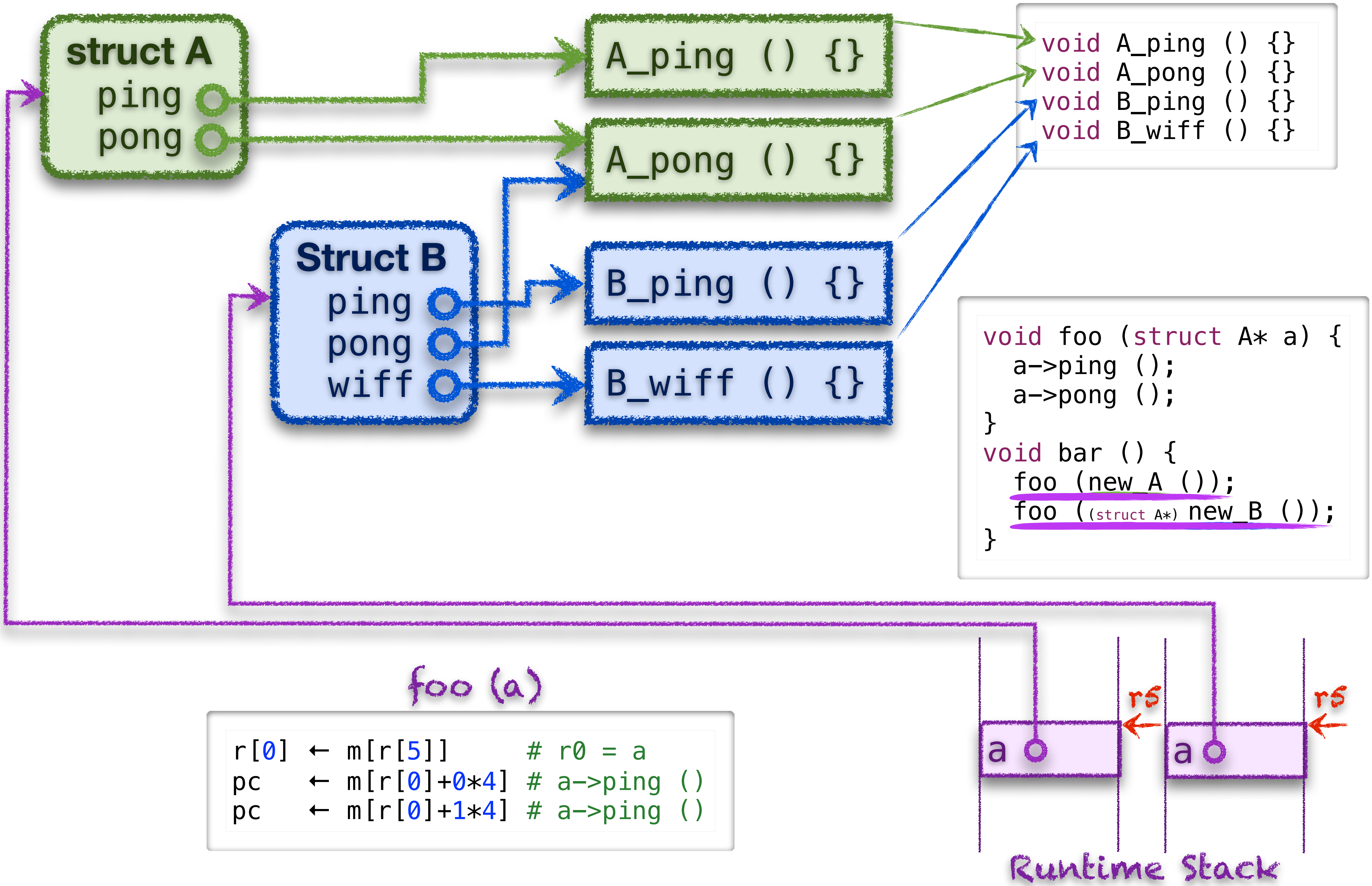

```
struct A {
  void (*ping) ();
  void (*pong) ();
};

struct A* new_A () {
  struct A* a = (struct A*) malloc (sizeof (struct A));
  a->ping = A_ping;
  a->pong = A_pong;
  return a;
}
```

```
struct B {
  void (*ping)();
  void (*pong)();
  void (*wiff)();
};

struct B* new_B () {
  struct B* b = (struct B*) malloc (sizeof (struct B));
  b->ping = B_ping;
  b->pong = A_pong;
  b->wiff = B_wiff;
  return b;
}
```

Dispatch Diagram for C (the dispatch)



ISA for Polymorphic Dispatch

```
void foo (struct A* a) {
  a->ping ();
  a->pong ();
}
```

```
r[0] ← m[r[5]]       # r0 = a
pc   ← m[r[1]+0*4] # a->ping ()
pc   ← m[r[1]+1*4] # a->ping ()
```

- How do we complie
  - `a->ping ()` ?
- Pseudo code
  - `pc ← m[r[1]+0*4]`
- Current jumps supported by ISA

Name	Semantics	Assembly	Machine
jump absolute	`pc ← a`	`j a`	`b--- aaaaaaaa`
indirect jump	`pc ← r[t] + (o==pp*2)`	`j o(rt)`	`ctpp`

- We will benefit from a new instruction in the is
  - that jumps to an address that is stored in memory

Double-indirect jump instruction (b+o)

- jump to address stored in memory using base+offset addressing

Name	Semantics	Assembly	Machine
jump absolute	`pc ← a`	`j a`	`b--- aaaaaaaa`
indirect jump	`pc ← r[t] + (o==pp*2)`	`j o(rt)`	`ctpp`
dbl-ind jump b+o	`pc ← m[r[t] + (o==pp*4)]`	`j *o(rt)`	`dtpp`

Question 1

- What is the difference between these two C snippets?

(1)

```
void foo () {printf ("foon\n";}

void go(void (*proc)()) {
  proc();
}

go (foo);
```

(2)

```
void foo () {printf ("foon\n";}

void go() {
  foo();
}

go();
```

- [A] (2) calls foo, but (1) does not
- [B] (1) is not valid C
- [C] (1) jumps to foo using a dynamic address and (2) a static address
- [D] They both call foo using dynamic addresses
- [E] They both call foo using static addresses

Now, implement proc() and foo() assembly code

Switch Statements

Switch Statement

```
int i;
int j;

void foo () {
  switch (i) {
    case 0:  j=10; break;
    case 1:  j=11; break;
    case 2:  j=12; break;
    case 3:  j=13; break;
    default: j=14; break;
  }
}
```

```
void bar () {
  if (i==0)
    j=10;
  else if (i==1)
    j = 11;
  else if (i==2)
    j = 12;
  else if (i==3)
    j = 13;
  else
    j = 14;
}
```

- Semantics the same as simplified nested if statements
  - where condition of each *if* tests the same variable
  - unless you leave the *break* the end of the case block
- So, why bother putting this in the language?
  - is it for humans, facilitate writing and reading of code?
  - is it for compilers, permitting a more efficient implementation?
- Implementing switch statements
  - we already know how to implement if statements; is there anything more to consider?

Human vs Compiler

- Benefits for humans
  - the syntax models a common idiom: choosing one computation from a set
- But, switch statements have interesting restrictions
  - case labels must be *static*, *cardinal* values
    - a cardinal value is a *number* that specifies a *position* relative to the beginning of an ordered set
    - for example, integers are cardinal values, but strings are not
  - case labels must be compared for equality to a single dynamic expression
    - some languages permit the expression to be an inequality
- Do these restrictions benefit humans?
  - have you ever wanted to do something like this?

```
switch (treeName) {
  case "larch":
  case "cedar":
  case "hemlock":
}
```

```
switch (i,j) {
  case i>0:
  case i==0 & j>a:
  case i<0 & j==a:
  default:
}
```

Why Compilers like Switch Statements

- Notice what we have
  - switch condition evaluates to a number
  - each case arm has a distinct number
- And so, the implementation has a simplified form
  - build a table with the address of every case arm, indexed by case value
  - switch by indexing into this table and jumping to matching case arm
- For example

```
switch (i) {
  case 0:  j=10; break;
  case 1:  j=11; break;
  case 2:  j=12; break;
  case 3:  j=13; break;
  default: j=14; break;
}
```

```
    label jumpTable[4] = { L0, L1, L2, L3 };
    if (i < 0 || i > 3) goto DEFAULT;
    goto jumpTable[i];
L0: j = 10;
    goto CONT;
L1: j = 11;
    goto CONT;
L2: j = 12;
    goto CONT;
L3: j = 13;
    goto CONT;
DEFAULT:
    j = 14;
    goto CONT;
CONT:
```

Happy Compilers mean Happy People

```
switch (i) {
  case 0:  j=10; break;
  case 1:  j=11; break;
  case 2:  j=12; break;
  case 3:  j=13; break;
  default: j=14; break;
}
```

```
    label jumpTable[4] = { L0, L1, L2, L3 };
    if (i >3) goto DEFAULT;
    goto jumpTable[i];
L0: j = 10;
    goto CONT;
L1: j = 11;
    goto CONT;
L2: j = 12;
    goto CONT;
L3: j = 13;
    goto CONT;
DEFAULT:
    j = 14;
    goto CONT;
CONT:
```

- Computation can be much more efficient
  - compare the running time to if-based alternative
- But, could it all go horribly wrong?
  - construct a switch statement where this implementation technique is a really bad idea
- Guidelines for writing efficient switch statements

```
if (i==0)
  j=10;
else if (i==1)
  j = 11;
else if (i==2)
  j = 12;
else if (i==3)
  j = 13;
else
  j = 14;
```

The basic implementation strategy

- General form of a switch statement

```
switch (<cond>) {
  case <label_i>: <code_i>        repeated 0 or more times
  default:        <code_default>  optional
}
```

- Naive implementation strategy

```
goto address of code_default if cond > max_label_value
goto jumptable[label_i]

statically: jumptable[label_i] = address of code_i forall label_i
```

- But there are two additional considerations
  - case labels are not always contiguous
  - the lowest case label is not always 0

Refining the implementation strategy

- Naive strategy

```
goto address of code_default if cond > max_label_value
goto jumptable[label_i]

statically: jumptable[label_i] = address of code_i forall label_i
```

- Non-contiguous case labels
  - what is the problem
  - what is the solution

```
switch (i) {
  case 0:  j=10; break;
  case 3:  j=13; break;
  default: j=14; break;
}
```

- Case labels not starting at 0
  - what is the problem
  - what is the solution

```
switch (i) {
  case 1000:  j=10; break;
  case 1001:  j=11; break;
  case 1002:  j=12; break;
  case 1003:  j=13; break;
  default:    j=14; break;
}
```

Implementing Switch Statements

- Choose strategy
  - use jump-table unless case labels are sparse or there are very few of them
  - use nested-if-statements otherwise
- Jump-table strategy
  - statically
    - build jump table for all label values between lowest and highest
  - generate code to
    - goto default if condition is less than minimum case label or greater than maximum
    - normalize condition to lowest case label
    - use jumptable to go directly to code selected case arm

```
goto address of code_default if cond < min_label_value
goto address of code_default if cond > max_label_value
goto jumptable[cond-min_label_value]

statically: jumptable[i-min_label_value] = address of code_i
    forall i: min_label_value <= i <= max_label_value
```

Snippet B: In template form

```
switch (i) {
  case 20:  j=10; break;
  case 21:  j=11; break;
  case 22:  j=12; break;
  case 23:  j=13; break;
  default:  j=14; break;
}
```

```
  label jumpTable[4] = { L20, L21, L22, L23 };
  if (i < 20) goto DEFAULT;
  if (i > 23) goto DEFAULT;
  goto jumpTable[i-20];
L20:
  j = 10;
  goto CONT;
L21:
  j = 11;
  goto CONT;
L22:
  j = 12;
  goto CONT;
L23:
  j = 13;
  goto CONT;
DEFAULT:
  j = 14;
  goto CONT;
CONT:
```

Snippet B: In Assembly Code

```
foo:      ld   $i, r0            # r0 = &i
          ld   0x0(r0), r0       # r0 = i
          ld   $0xffffffed, r1   # r1 = -19
          add  r0, r1            # r0 = i-19
          bgt  r1, l0            # goto l0 if i>19
          br   default           # goto default if i<20
l0:       ld   $0xffffffe9, r1   # r1 = -23
          add  r0, r1            # r1 = i-23
          bgt  r1, default       # goto default if i>23
          ld   $0xffffffec, r1   # r1 = -20
          add  r1, r0            # r0 = i-20
          ld   $jmptable, r1     # r1 = &jmptable
          j    *(r1, r0, 4)      # goto jmptable[i-20]
```

```
case20:   ld   $0xa, r1          # r1 = 10
          br   done              # goto done
...
default:  ld   $0xe, r1          # r1 = 14
          br   done              # goto done
done:     ld   $j, r0            # r0 = &j
          st   r1, 0x0(r0)       # j = r1
          br   cont              # goto cont
```

```
jmptable: .long 0x00000140       # & (case 20)
          .long 0x00000148       # & (case 21)
          .long 0x00000150       # & (case 22)
          .long 0x00000158       # & (case 23)
```

Simulator ...

Static and Dynamic Control Flow

Jump instructions

- specify a *target address* and a *jump-taken condition*
- target address can be static or dynamic
- jump-target condition can be static (unconditional) or dynamic (conditional)

Static jumps

- jump target address is static
- compiler hard-codes this address into instruction

Name	Semantics	Assembly	Machine
branch	`pc ← (a==pc+oo*2)`	`br a`	`8-oo`
branch if equal	`pc ← (a==pc+oo*2) if r[c]==0`	`beq a`	`9coo`
branch if greater	`pc ← (a==pc+oo*2) if r[c]>0`	`bgt a`	`acoo`
jump	`pc ← a`	`j a`	`b--- aaaaaaaa`

Dynamic jumps

- jump target address is dynamic

Dynamic Jumps

- Indirect Jump
  - Jump target address stored in a register
  - We already introduced this instruction, but used it for ***static*** procedure calls

Name	Semantics	Assembly	Machine
indirect jump	`pc ← r[t] + (o==pp*2)`	`j o(rt)`	`ctpp`

- Double indirect jumps
  - Jump target address stored in memory
  - Base-plus-displacement and indexed modes for memory acecss

Name	Semantics	Assembly	Machine
dbl-ind jump b+o	`pc ← m[r[t] + (o==pp*2)]`	`j *o(rt)`	`dtpp`
dbl-ind jump indexed	`pc ← m[r[t] + r[i]*4]`	`j *(rt,ri,4)`	`eti-`

Question 2

- What happens when this code is compiled and run?

```
void foo (int i) {printf ("foo %d\n", i);}
void bar (int i) {printf ("bar %d\n", i);}
void bat (int i) {printf ("bat %d\n", i);}

void (*proc[3])() = {foo, bar, bat};

int main (int argv, char** argc) {
  int input;
  if (argv==2) {
    input = atoi (argc[1]);
    proc[input] (input+1);
  }
}
```

- [A] It does not compile
- [B] For any value of input it generates an error
- [C] If input is 1 it prints “bat 1” and it does other things for other values
- [D] If input is 1 it prints “bar 2” and it does other things for other values

Question 3

- What happens when this code is compiled and run?

```
void foo (int i) {printf ("foo %d\n", i);}
void bar (int i) {printf ("bar %d\n", i);}
void bat (int i) {printf ("bat %d\n", i);}

void (*proc[3])(int) = {foo, bar, bat};

int main (int argv, char** argc) {
  int input;
  if (argv==2) {
    input = atoi (argc[1]);
    proc[input] (input+1);
  }
}
```

- [A] It does not compile
- [B] For any value of input it generates an error
- [C] If input is 1 it prints “bat 1” and it does other things for other values
- [D] If input is 1 it prints “bar 2” and it does other things for other values

Question 4

- Which implements **`proc[input] (input+1);`**
  - [A]

```
ld      (r5), r0
ld      $proc, r1
deca    r5
mov     r0, r2
inc     r2
st      r2, (r5)
gpc     $2, r6
j       *(r1, r0, 4)
```

  - [B]

```
ld      (r5), r0
ld      $proc, r1
deca    r5
mov     r0, r2
inc     r2
st      r2, (r5)
gpc     $6, r6
j       bar
```

```
void foo (int i) {printf ("foo %d\n", i);}
void bar (int i) {printf ("bar %d\n", i);}
void bat (int i) {printf ("bat %d\n", i);}

void (*proc[3])(int) = {foo, bar, bat};

int main (int argv, char** argc) {
  int input;
  if (argv==2) {
    input = atoi (argc[1]);
    proc[input] (input+1);
  }
}
```

  - [C] I think I understand this, but I can’t really read the assembly code.
  - [D] Are you serious? I have no idea.

Summary

- Static vs Dynamic flow control
  - static if jump target is known by compiler
  - dynamic for polymorphic dispatch, function pointers, and switch statements
- Polymorphic Dispatch in Java
  - invoking a method on an object in java
  - method address depends on object's type, which is not know statically
  - object has pointer to class object; class object contains method jump table
  - procedure call is this a double-indirect jump – i.e., target address in memory
- Function Pointers in C
  - a variable that stores the address of a procedure
  - used to implement dynamic procedure call, similar to polymorphic dispatch
- Switch Statements
  - syntax restricted so that they can be implemented with jump table
  - jump-table implementation running time is independent of the number of case labels
  - but, only works if case label values are reasonably dense