Declare Your Language

Chapter 10:
Virtual Machines & Code Generation

Eelco Visser

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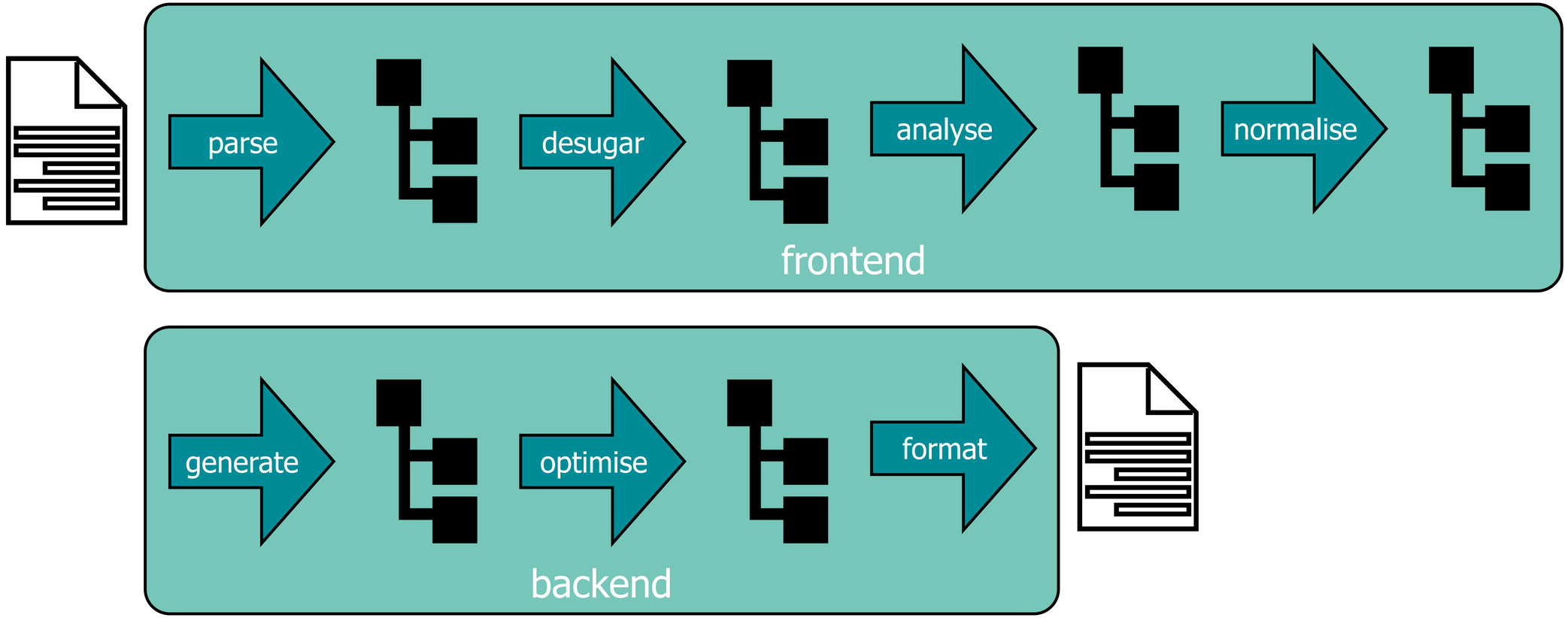
Virtual Machines & Code Generation



Outline

Linguistic Abstraction

- High-level programming languages abstract from low-level machine mechanics
- Abstractions in imperative and object-oriented languages
- Calling Conventions
- Register machines vs stack machines

Java Virtual Machine

- Architecture
- Operation stack
- Constant pool
- Local variables
- Heap
- Stack frames
- Class files

Code Generation Mechanics

- Printing strings
- String concatenation
- String interpolation
- Transformation

Reading Material

The Java® Virtual Machine Specification

Java SE 8 Edition

Tim Lindholm
Frank Yellin
Gilad Bracha
Alex Buckley

2015-02-13

Literature: VMs & Compilation

Java Virtual Machine

Tim Lindholm, Frank Yellin: The Java Virtual Machine Specification, 2nd edition. Addison-Wesley, 1999.

Bill Venners: Inside the Java 2 Virtual Machine. McGraw-Hill, 2000.

Activation Records

Andrew W. Appel, Jens Palsberg: Modern Compiler Implementation in Java, 2nd edition. 2002

Literature: Semantics of Programming Languages

Imperative Languages

- Carl A. Gunter: Semantics of Programming Languages: Structures and Techniques. MIT Press, 1992
- Kenneth C. Louden: Programming Languages: Principles and Practice. Course Technology, 2002

Object-Oriented Languages

- Martin Abadi, Luca Cardelli: A Theory of Objects. Springer, 1996.
- Kim B. Bruce: Foundations of Object-Oriented Programming Languages: Types and Semantics. MIT Press, 2002.
- Timothy Budd: An Introduction to Object-Oriented Programming. Addison-Wesley, 2002.

State & Control

State

Machine state

- a pile of data stored in memory
- memory hierarchy: registers, RAM, disk, network, …

Imperative program

- computation is series of changes to memory
- basic operations on memory (increment register)
- controlling such operations (jump, return address, …)
- control represented by state (program counter, stack, …)

Registers: x86 Family

General purpose registers

- accumulator AX - arithmetic operations
- counter CX - shift/rotate instructions, loops
- data DX - arithmetic operations, I/O
- base BX - pointer to data
- stack pointer SP, base pointer BP - top and base of stack
- source SI, destination DI - stream operations

Special purpose registers

- segments SS, CS, DS, ES, FS, GS
- flags EFLAGS

Example: x86 Assembler

```
    mov AX [1]          read memory

    mov CX AX

L:  dec CX
    mul CX              calculation
    cmp CX 1
    ja  L               jump

    mov [2] AX          write memory
```

Example: Java Bytecode

```
.method static public m(I)I

        iload 1
        ifne else
        iconst_1
        ireturn

else:   iload 1
        dup
        iconst_1
        isub
        invokestatic Math/m(I)I
        imul
        ireturn
```

jump

read memory

calculation

Memory & Control Abstractions

Memory abstractions

- variables: abstract over data storage
- expressions: combine data into new data
- assignment: abstract over storage operations

Control-flow abstractions

- structured control-flow: abstract over unstructured jumps
- ‘go to statement considered harmful’ Edgser Dijkstra, 1968

Example: C

```
int f = 1
int x = 5
int s = f + x
```

variable

expression

```
while (x > 1) {
   f = x * f ;
   x = x - 1
}
```

control flow

assignment

Example: Tiger

```
/* factorial function */

let
   var f := 1
   var x := 5
   var s := f + x
in
   while x > 1 do (
      f := x * f ;
      x := x - 1
   )
end
```

variable

expression

control flow

assignment

Procedures

Procedural Abstraction

Control-flow abstraction

- Procedure: named unit of computation
- Procedure call: jump to unit of computation and return

Memory abstraction

- Formal parameter: the name of the parameter
- Actual parameter: value that is passed to procedure
- Local variable: temporary memory

Recursion

- Procedure may (indirectly) call itself
- Consequence?

Example: Procedures in C

```c
#include <stio.h>

/* factorial function */
int fac( int num ) {
    if (num < 1)
        return 1;
    else
        return num * fac(num - 1) ;
}
```

formal parameter

recursive call

```c
int main() {
    int x = 10 ;

    int f = fac( x ) ;
    int x printf(“%d! = %d\n”, x, f);
    return 0;
}
```

local variable

actual parameter

Procedures in Tiger

```
/* factorial function */

let
    function fac( n: int ) : int =
        let
            var f := 1
        in
            if n < 1 then
                f := 1
            else
                f := (n * fac(n - 1) );
            f
        end
    var f := 0
    var x := 5
in
    f := fac( x )
end
```

formal parameter

local variable

recursive call

actual parameter

Implementing Procedures with Stack and Stack Frames

Stack

- temporary storage
- grows from high to low memory addresses
- starts at SS

Stack frames

- return address
- local variables
- parameters
- stack base: BP
- stack top: SP

Reminder: Registers in x86 Family

General purpose registers

- accumulator AX - arithmetic operations
- counter CX - shift/rotate instructions, loops
- data DX - arithmetic operations, I/O
- base BX - pointer to data
- stack pointer SP, base pointer BP - top and base of stack
- source SI, destination DI - stream operations

Special purpose registers

- segments SS, CS, DS, ES, FS, GS
- flags EFLAGS

Example: Procedures in x86 Assembler

```
push 21
push 42
call _f
add  SP 8
```

pass parameter

free parameters

```
push BP
mov  BP SP
mov  AX [BP + 8]
mov  DX [BP + 12]
add  AX DX
pop  BP
ret
```

new stack frame

access parameter

old stack frame

Calling Conventions: CDECL

Caller

- push parameters right-to-left on the stack
- clean-up stack after call

```
push 21
push 42
call _f
add  ESP 8
```

Callee

- save old BP
- initialise new BP
- save registers
- return result in AX
- restore registers
- restore BP

```
push EBP
mov  EBP ESP
mov  EAX [EBP + 8]
mov  EDX [EBP + 12]
add  EAX EDX
pop  EBP
ret
```

Calling Conventions: STDECL

caller

- push parameters right-to-left on the stack

```
push 21
push 42
call _f@8
```

callee

- save old BP
- initialise new BP
- save registers
- return result in AX
- restore registers
- restore BP

```
push EBP
mov  EBP ESP
mov  EAX [EBP + 8]
mov  EDX [EBP + 12]
add  EAX EDX
pop  EBP
ret  8
```

Calling Conventions: FASTCALL

Caller

- passes parameters in registers
- pushes additional parameters right-to-left on the stack

```
mov  ECX 21
mov  EDX 42
call @f@8
```

Callee

- save old BP, initialise new BP
- save registers
- return result in AX
- restore registers
- restore BP
- cleans up the stack

```
push EBP
mov  EBP ESP
mov  EAX ECX
add  EAX EDX
pop  EBP
ret
```

Calling Conventions

Procedure declarations

- in principle: full freedom
- project constraints
- target platform constraints

Procedure calls

- need to match procedure declarations

Precompiled libraries

- avoid recompilation
- source code not always available

Standardization

- compilers / high-level languages standardize use of calling conventions
- portable code: does not depend on particular calling convention

Object-Oriented Languages (home work)

Modularity: Objects & Messages

Objects

- generalisation of records
- identity
- state
- behaviour

Messages

- objects send and receive messages
- trigger behaviour
- imperative realisation: method calls

Modularity: Classes

Classes

- generalisation of record types
- characteristics of objects: attributes, fields, properties
- behaviour of objects: methods, operations, features

Encapsulation

- interface exposure
- hide attributes & methods
- hide implementation

```
public class C {
   public int f1;
   private int f2;
   public void m1() { return; }
   private C m2(C c) { return c; }
}
```

Inheritance vs Interfaces

Inheritance

- inherit attributes & methods
- additional attributes & methods
- override behaviour
- nominative subtyping

Interfaces

- avoid multiple inheritance
- interface: contract for attributes & methods
- class: provide attributes & methods
- nominative subtyping

```
public class C {
   public int f1;
   public void m1() {…}
   public void m2() {…}
}

public class D extends C {
   public int f2;
   public void m2() {…}
   public void m3() {…}
}

public interface I {
   public int f;
   public void m();
}

public class E implements I {
   public int f;
   public void m() {…}
   public void m'() {…}
}
```

Polymorphism

Ad-hoc polymorphism

- overloading
  - same method name, independent classes
  - same method name, same class, different parameter types
- overriding
  - same method name, subclass, compatible types

Universal polymorphism

- subtype polymorphism
  - inheritance, interfaces
- parametric polymorphism

Static vs. Dynamic Dispatch

Dispatch

- link method call to method

Static dispatch

- type information at compile-time

Dynamic dispatch

- type information at run-time
- single dispatch: one parameter
- multiple dispatch: more parameters

Single Dispatch in Java

```
public class A {} public class B extends A {} public class C extends B {}

public class D {
   public A m(A a) { System.out.println("D.m(A a)"); return a; }
   public A m(B b) { System.out.println("D.m(B b)"); return b; }
}

public class E extends D {
   public A m(A a) { System.out.println("E.m(A a)"); return a; }
   public B m(B b) { System.out.println("E.m(B b)"); return b; }
}
```

```
A a = new A(); B b  = new B(); C c  = new C(); D d = new D(); E e  = new E();
               A ab = b;       A ac = c;                      D de = e;

d. m(a); d. m(b); d. m(ab); d. m(c); d. m(ac);
e. m(a); e. m(b); e. m(ab); e. m(c); e. m(ac);
de.m(a); de.m(b); de.m(ab); de.m(c); de.m(ac);
```

Overriding

Methods

- parameter types
- return type

Covariance

- method in subclass
- return type: subtype of original return type

Contravariance

- method in subclass
- parameter types: supertypes of original parameter types

Overloading vs Overriding

```
public class F {
   public A m(B b) { System.out.println("F.m(B b)"); return b; }
}

public class G extends F {
   public A m(A a) { System.out.println("G.m(A a)"); return a; }
}

public class H extends F {
   public B m(B b) { System.out.println("H.m(B b)"); return b; }
}
```

```
A a = new A(); B b  = new B(); F f = new F(); G g = new G(); H h = new H();
               A ab = b;

f.m(b);
g.m(a); g.m(b); g.m(ab);
h.m(a); h.m(b); h.m(ab);
```

Invariance

```
public class X {
   public A a;
   public A    getA()    { return a ; }
   public void setA(A a) { this.a = a ; }
}

public class Y extends X {
   public B a;
   public B    getA()    { return a ; }
   public void setA(B a) { this.a = a ; }
}
```

```
A a = new A(); B b  = new B(); X y = new Y();

y.getA(); y.setA(b); y.setA(a);

String[] s = new String[3] ; Object[] o = s ; o[1] = new A();
```

Summary: Abstractions

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Abstractions for Memory and Control

Imperative languages

- subroutines, routines, procedures, functions, methods
- scoping: local variables
- declarations with parameters (formal parameters)
- calls with arguments (actual parameters)
- pass by value, pass by reference

Machine code

- jumps: call and return
- call stack: return address, parameters, private data
- procedure prologue and epilogue

Imperative vs Object-Oriented

Imperative languages

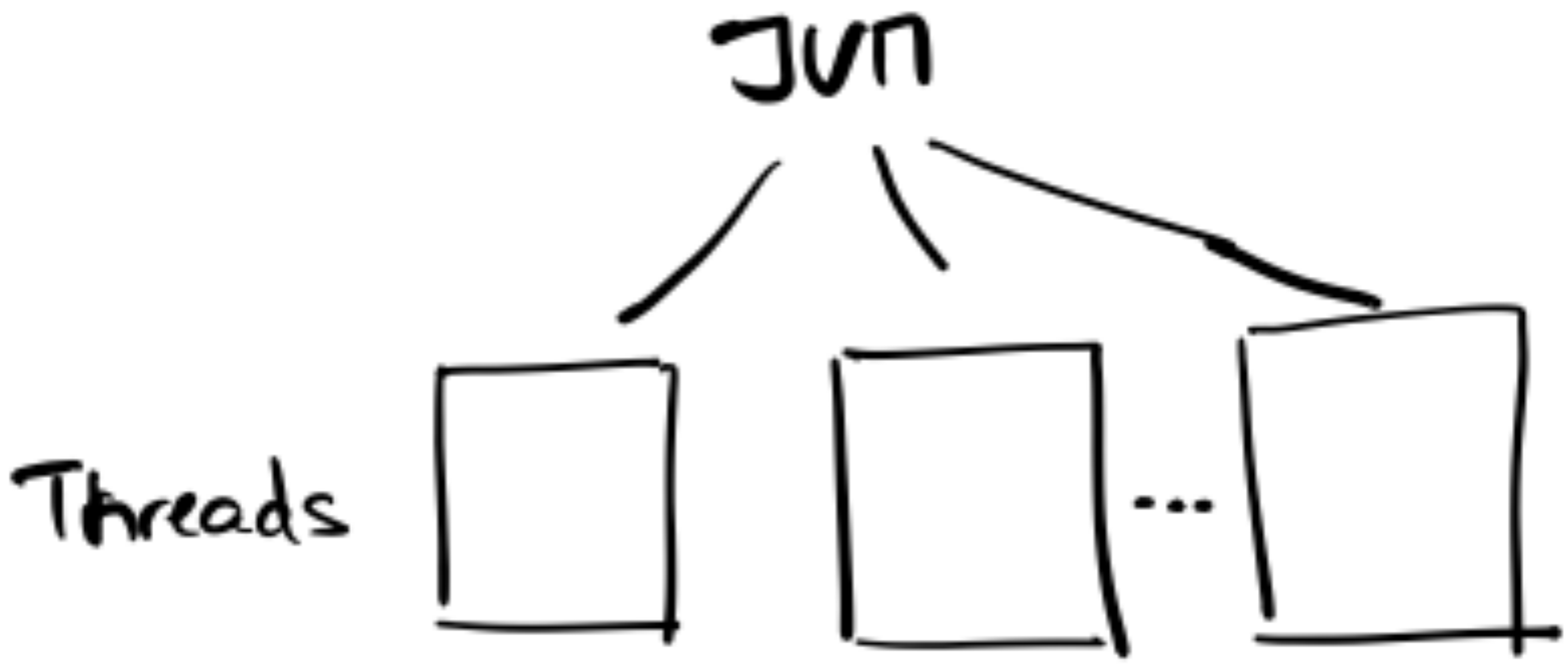
- state & statements
- abstraction over machine code
- control flow & procedures
- types

Object-oriented languages

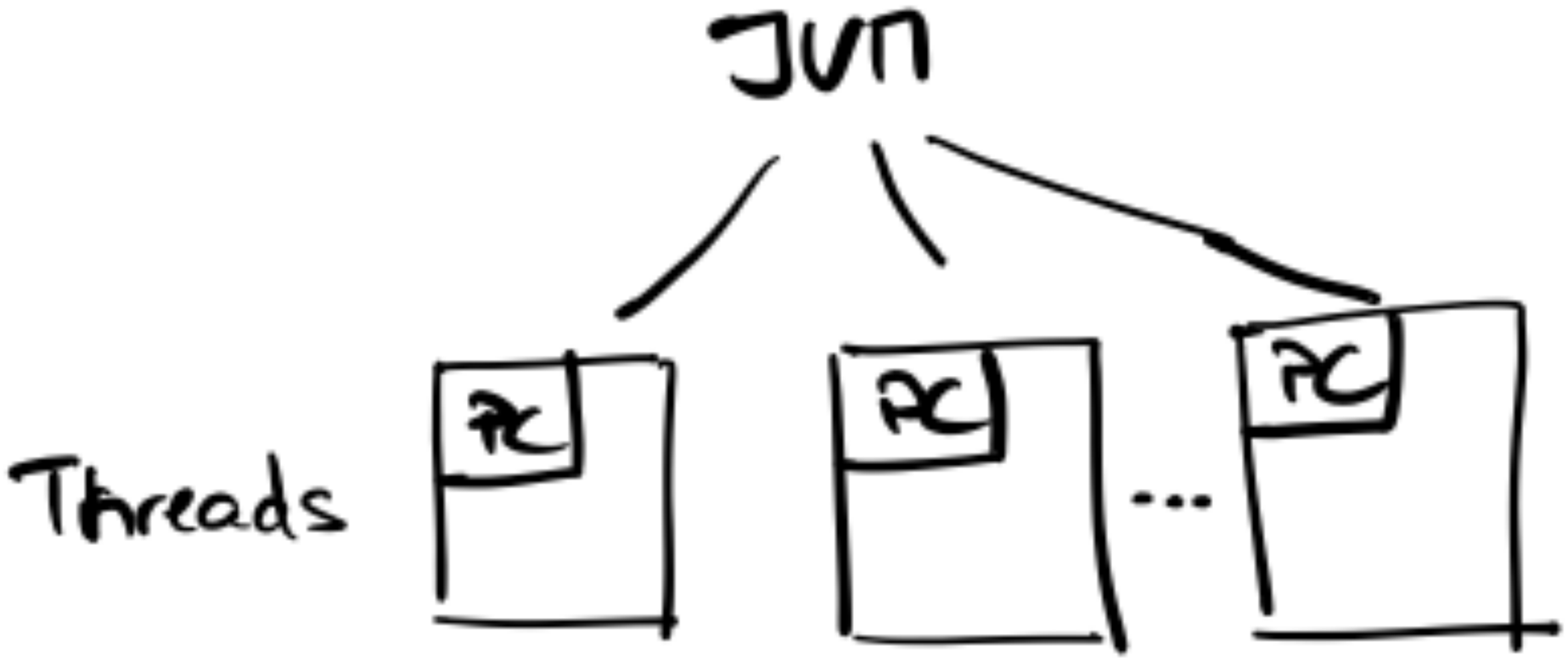
- objects & messages
- classes
- inheritance
- types

Java Virtual Machine: Architecture

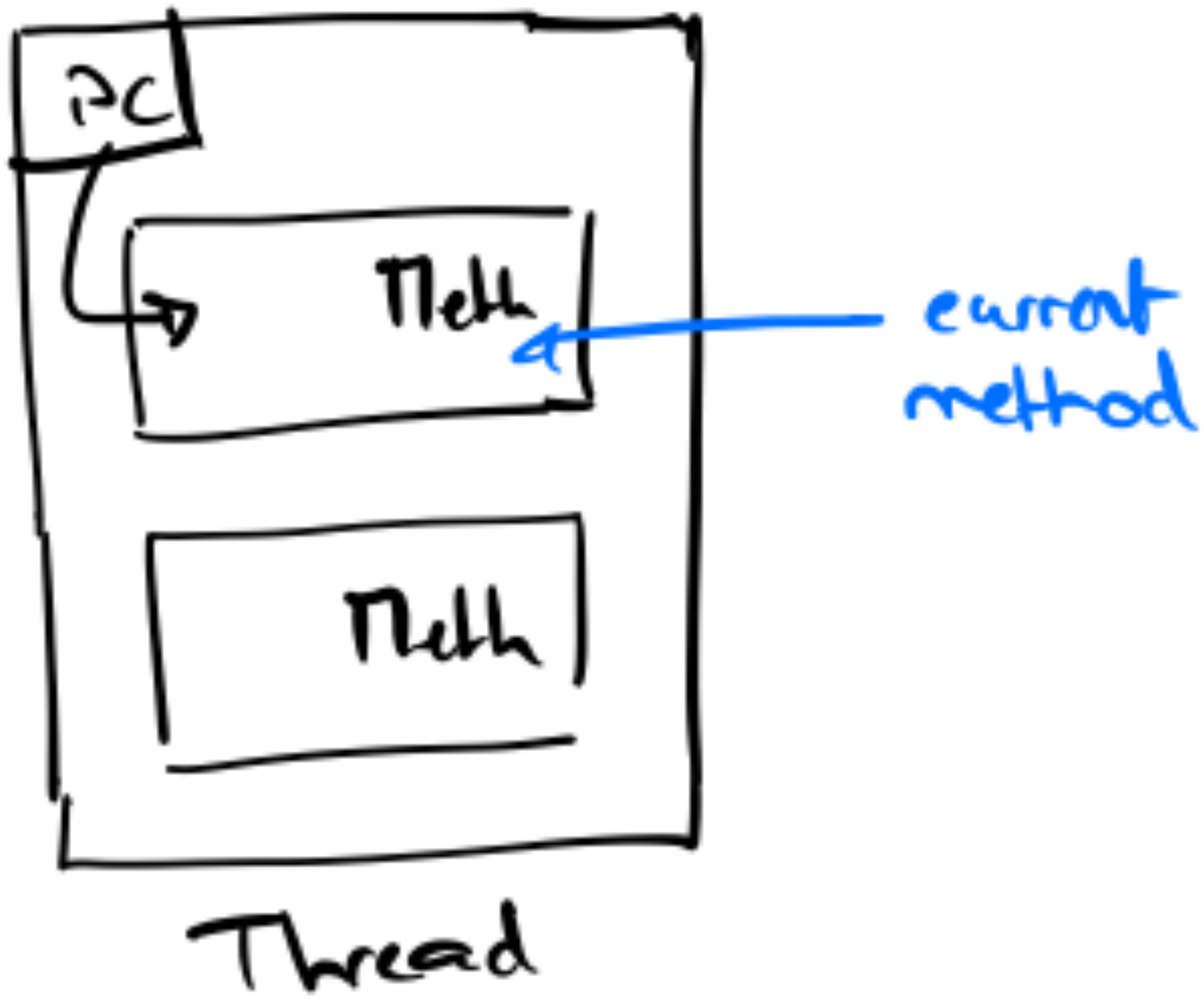
JVM Architecture



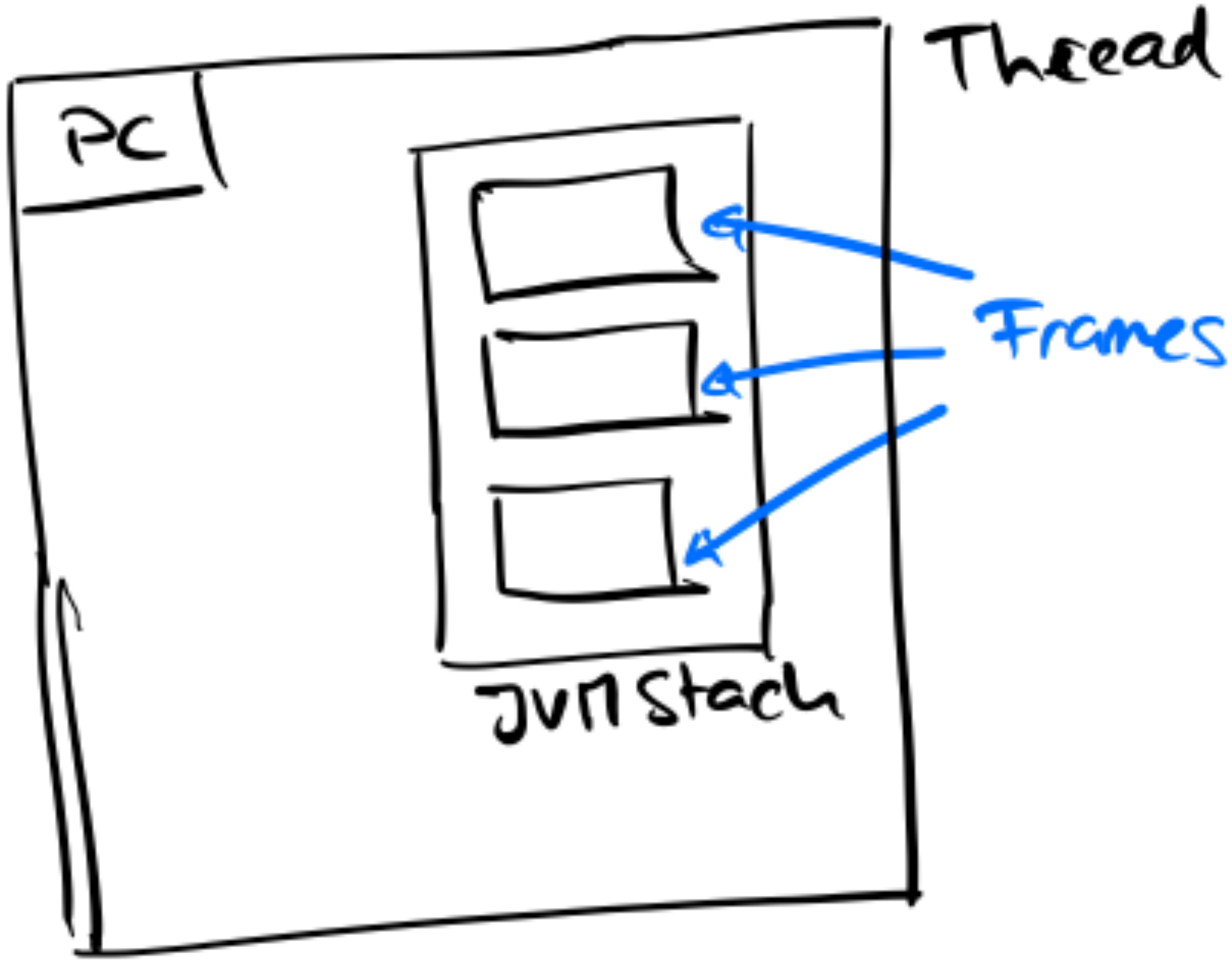
JVM Architecture: Threads



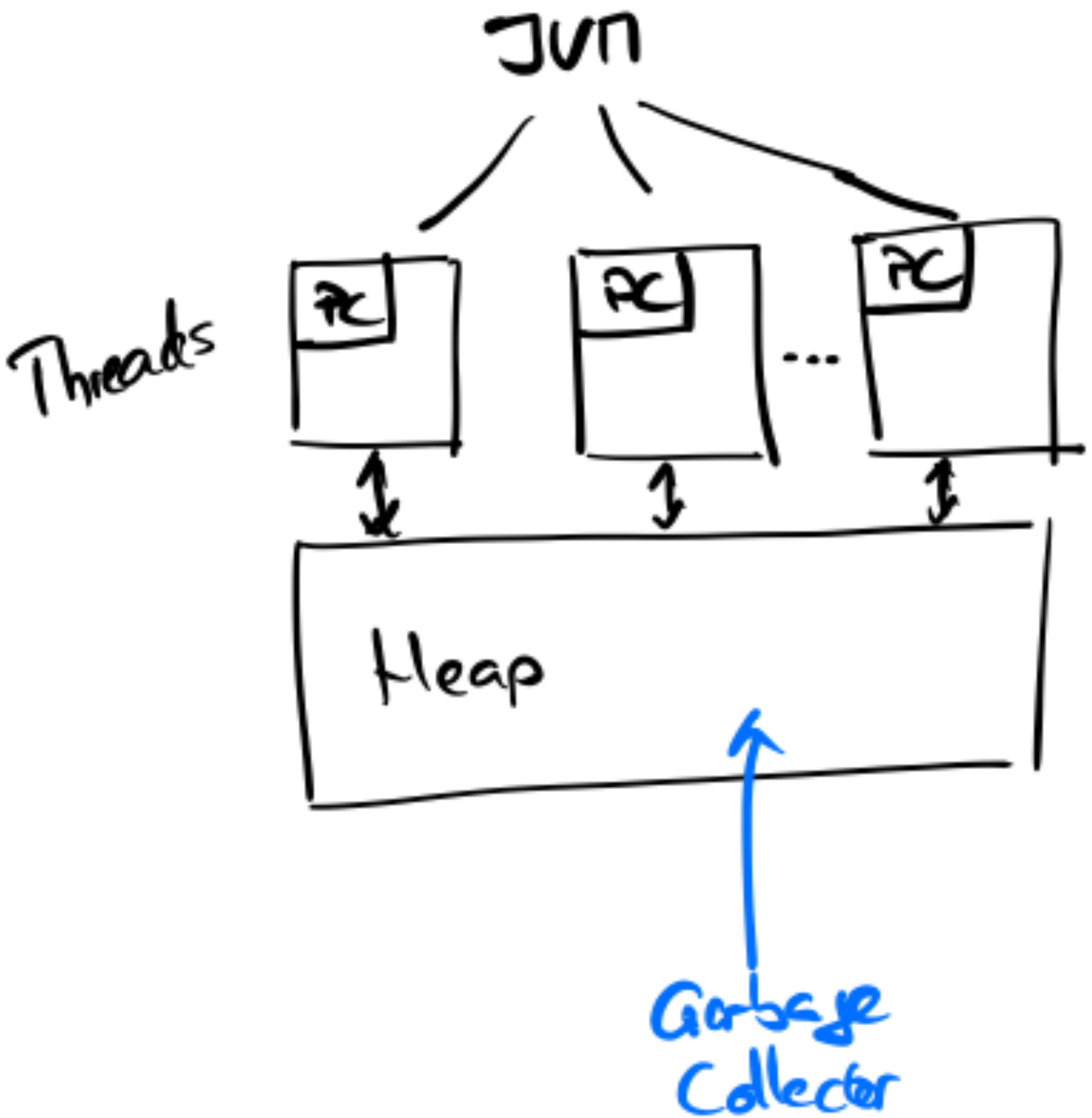
JVM Architecture: Thread



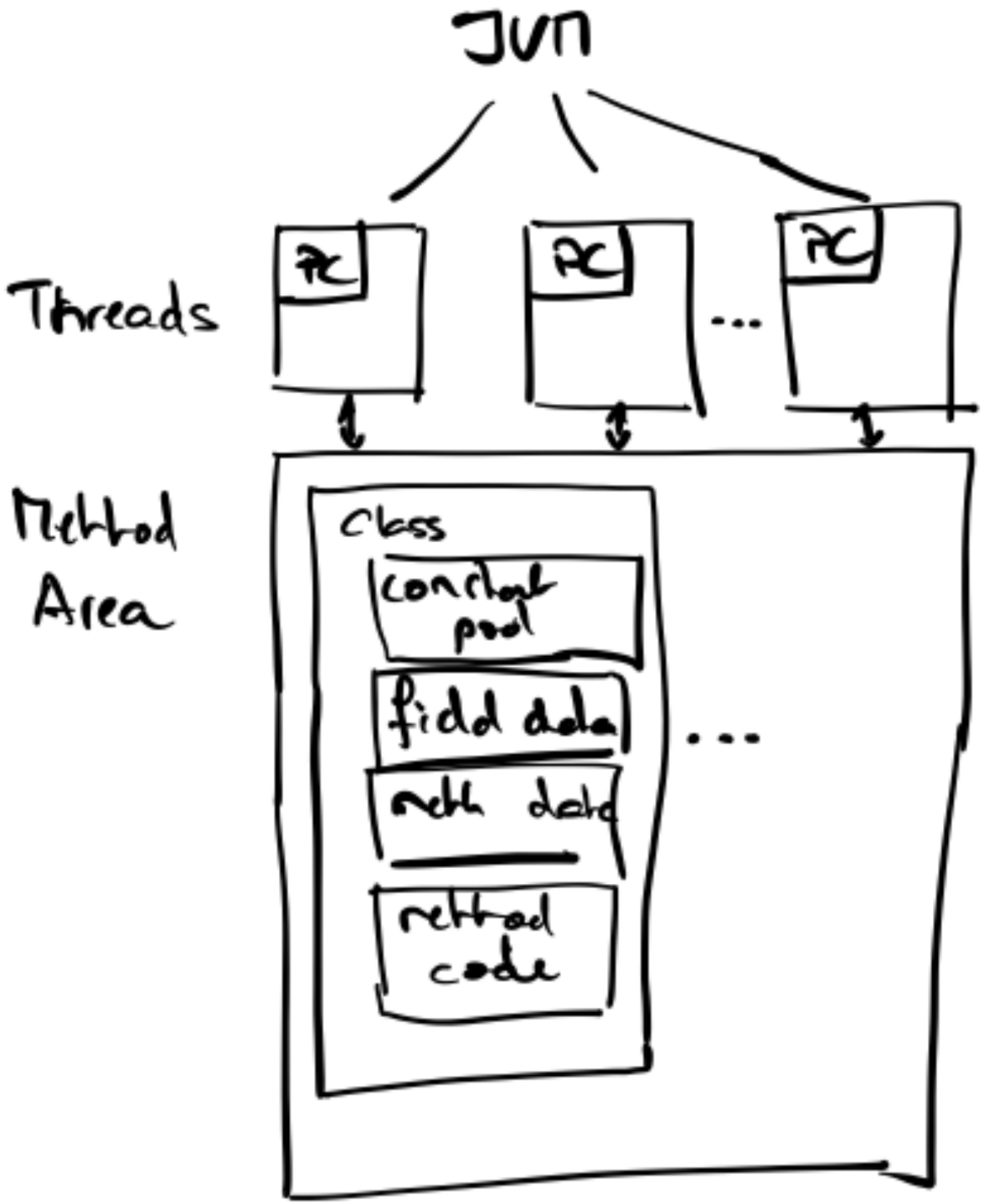
JVM Architecture: Stack



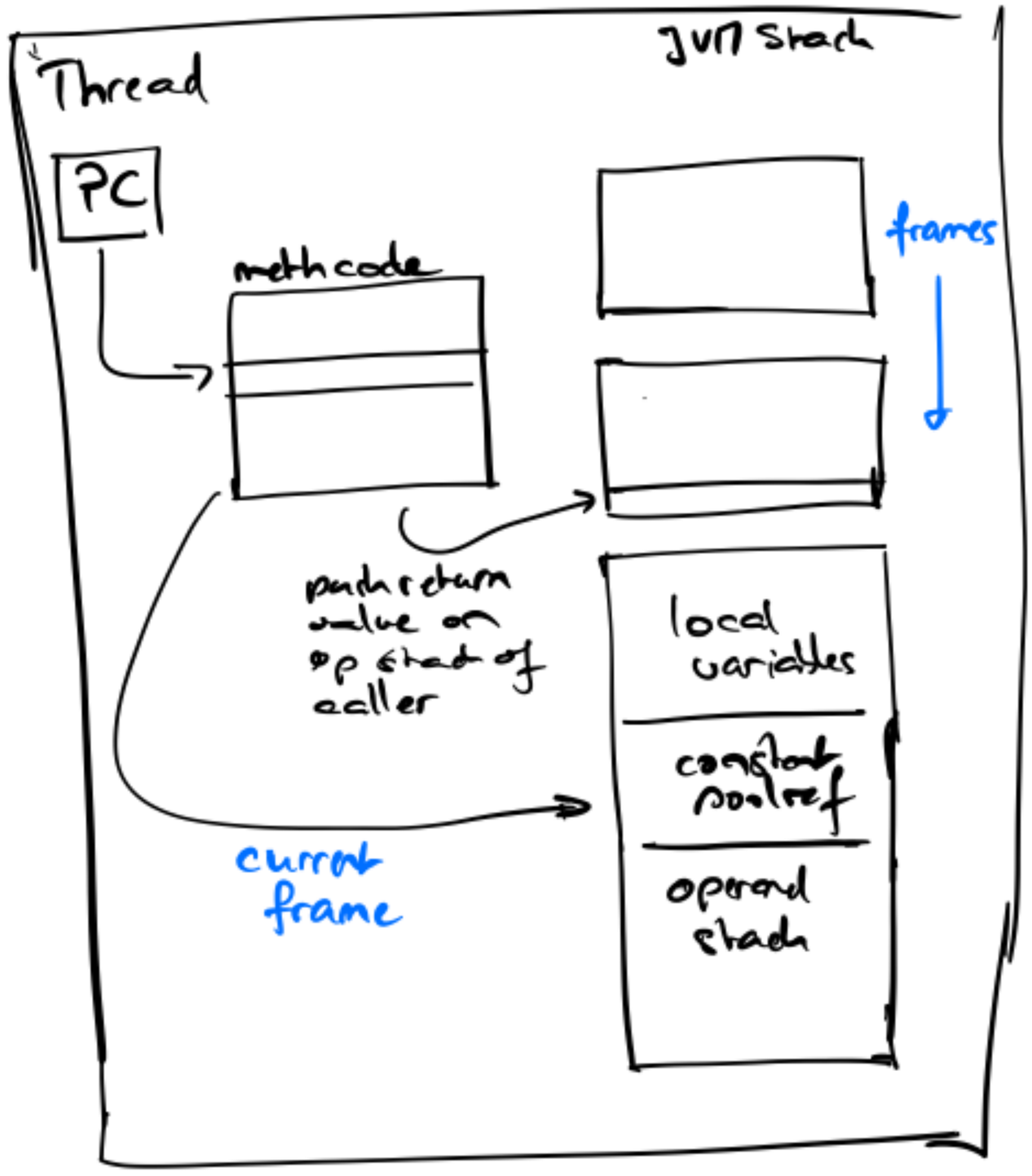
JVM Architecture: Heap



JVM Architecture: Method Area



JVM Architecture: JVM Stack



Reverse Engineering the JVM Instruction Set

JVM: Control Flow

Bytecode Instructions: Goto

method area		
pc: 00		
00	A7	goto
01	00	
02	04	04
03	00	nop
04	A7	goto
05	FF	
06	FF	03

Bytecode Instructions: Goto

method area		
pc: 04		
00	A7	goto
01	00	
02	04	04
03	00	nop
04	A7	goto
05	FF	
06	FF	03

Bytecode Instructions: Goto

method area		
pc: 03		
00	A7	goto
01	00	
02	04	04
03	00	nop
04	A7	goto
05	FF	
06	FF	03

Bytecode Instructions: Goto

method area		
pc: 04		
00	A7	goto
01	00	
02	04	04
03	00	nop
04	A7	goto
05	FF	
06	FF	03

JVM: Operand Stack

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Operand Stack

method area	
pc: 00	
00	04 iconst_1
01	05 iconst_2
02	10 bipush
03	2A
04	11 sipush
05	43
06	03

stack
optop: 00
00
01
02
03
04
05
06

Operand Stack

method area	
pc: 01	
00	04 iconst_1
01	05 iconst_2
02	10 bipush
03	2A
04	11 sipush
05	43
06	03

stack
optop: 01
00 0000 0001
01
02
03
04
05
06

Operand Stack

method area	
pc: 02	
00	04 iconst_1
01	05 iconst_2
02	10 bipush
03	2A
04	11 sipush
05	43
06	03

stack	
optop: 02	
00	0000 0001
01	0000 0002
02	
03	
04	
05	
06	

Operand Stack

method area

pc: 04

00	04	iconst_1
01	05	iconst_2
02	10	bipush
03	2A	
04	11	sipush
05	43	
06	03	

stack

optop: 03

00	0000 0001
01	0000 0002
02	0000 002A
03	
04	
05	
06	

Operand Stack

method area	
pc: 07	
00	04 iconst_1
01	05 iconst_2
02	10 bipush
03	2A
04	11 sipush
05	43
06	03

stack	
optop: 04	
00	0000 0001
01	0000 0002
02	0000 002A
03	0000 4303
04	
05	
06	

Operand Stack

method area	
pc: 07	
07	60 iadd
08	68 imul
09	5F swap
0A	64 isub
0B	9A ifne
0C	FF
0D	F5 00

stack	
optop: 04	
00	0000 0001
01	0000 0002
02	0000 002A
03	0000 4303
04	
05	
06	

Operand Stack

method area	
pc: 08	
07	60 iadd
08	68 imul
09	5F swap
0A	64 isub
0B	9A ifne
0C	FF
0D	F5 00

stack	
optop: 03	
00	0000 0001
01	0000 0002
02	0000 432D
03	
04	
05	
06	

Operand Stack

method area	
pc: 09	
07	60 iadd
08	68 imul
09	5F swap
0A	64 isub
0B	9A ifne
0C	FF
0D	F5 00

stack	
optop: 02	
00	0000 0001
01	0000 865A
02	
03	
04	
05	
06	

Operand Stack

method area	
pc: 0A	
07	60 iadd
08	68 imul
09	5F swap
0A	64 isub
0B	9A ifne
0C	FF
0D	F5 00

stack	
optop: 02	
00	0000 865A
01	0000 0001
02	
03	
04	
05	
06	

Operand Stack

method area	
pc: 0B	
07	60 iadd
08	68 imul
09	5F swap
0A	64 isub
0B	9A ifne
0C	FF
0D	F5 00

stack
optop: 01
00 0000 8659
01
02
03
04
05
06

Operand Stack

method area	
pc: 00	
00	04 iconst_1
01	05 iconst_2
02	10 bipush
03	2A
04	11 sipush
05	43
06	03

stack
optop: 00
00
01
02
03
04
05
06

JVM: Constant Pool

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Constant Pool

method area		stack
pc: 00	constant pool	optop: 00
00 12 ldc	00 0000 002A	00
01 00 00	01 0000 4303	01
02 12 ldc	02 0000 0000	02
03 01 01	03 0000 002A	03
04 14 ldc2_w	04	04
05 00	05	05
06 02 02	06	06

Constant Pool

method area		stack
pc: 02	constant pool	optop: 01
00 12 ldc	00 0000 002A	00 0000 002A
01 00 00	01 0000 4303	01
02 12 ldc	02 0000 0000	02
03 01 01	03 0000 002A	03
04 14 ldc2_w	04	04
05 00	05	05
06 02 02	06	06

Constant Pool

method area			constant pool		stack		
pc: 04					optop: 02		
00	12	ldc	00	0000 002A	00	0000 002A	
01	00	00	01	0000 4303	01	0000 4303	
02	12	ldc	02	0000 0000	02		
03	01	01	03	0000 002A	03		
04	14	ldc2_w	04		04		
05	00		05		05		
06	02	02	06		06		

Constant Pool

method area

pc: 07

00 12 ldc	00 0000 002A
01 00 00	01 0000 4303
02 12 ldc	02 0000 0000
03 01 01	03 0000 002A
04 14 ldc2_w	04
05 00	05
06 02 02	06

constant pool

stack

optop: 04

00 0000 002A
01 0000 4303
02 0000 0000
03 0000 002A
04
05
06

JVM: Local Variables

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Local Variables

method area		
pc: 00		
00	04	iconst_1
01	3B	istore_0
02	1A	iload_0
03	3C	istore_1
04	84	iinc
05	01	01
06	01	01

stack	
optop: 00	local variables
00	00
01	01
02	02
03	03
04	04
05	05
06	06

Local Variables

method area		
pc: 01		
00	04	iconst_1
01	3B	istore_0
02	1A	iload_0
03	3C	istore_1
04	84	iinc
05	01	01
06	01	01

stack	
optop: 01	local variables
00 0000 0001	00
01	01
02	02
03	03
04	04
05	05
06	06

Local Variables

method area		
pc: 02		
00	04	iconst_1
01	3B	istore_0
02	1A	iload_0
03	3C	istore_1
04	84	iinc
05	01	01
06	01	01

stack	
optop: 00	local variables
00	00 0000 0001
01	01
02	02
03	03
04	04
05	05
06	06

Local Variables

method area

pc: 03

00	04	iconst_1
01	3B	istore_0
02	1A	iload_0
03	3C	istore_1
04	84	iinc
05	01	01
06	01	01

stack

optop: 01

	local variables
00 0000 0001	00 0000 0001
01	01
02	02
03	03
04	04
05	05
06	06

Local Variables

method area		
pc: 04		
00	04	iconst_1
01	3B	istore_0
02	1A	iload_0
03	3C	istore_1
04	84	iinc
05	01	01
06	01	01

stack	
optop: 00	local variables
00	00 0000 0001
01	01 0000 0001
02	02
03	03
04	04
05	05
06	06

Local Variables

method area		
pc: 07		
00	04	iconst_1
01	3B	istore_0
02	1A	iload_0
03	3C	istore_1
04	84	iinc
05	01	01
06	01	01

stack	
optop: 00	local variables
00	00 0000 0001
01	01 0000 0002
02	02
03	03
04	04
05	05
06	06

JVM: Heap

Heap

method area	
pc: 00	constant pool
00 12 ldc	00 4303 4303
01 00 00	01 0000 0004
02 19 aload	02
03 00 00	03
04 12 ldc	04
05 01 01	05
06 2E iaload	06

stack	
optop: 00	local variables
00	00 002A 002A
01	01
02	02
03	03
04	04
05	05
06	06

heap	
4303 4303 "Compilers"	002A 002A [20,01,40,02,42]

Heap

method area	
pc: 02	constant pool
00 12 ldc	00 4303 4303
01 00 00	01 0000 0004
02 19 aload	02
03 00 00	03
04 12 ldc	04
05 01 01	05
06 2E iaload	06

stack	
optop: 01	local variables
00 4303 4303	00 002A 002A
01	01
02	02
03	03
04	04
05	05
06	06

heap	
4303 4303 "Compilers"	002A 002A [20,01,40,02,42]

Heap

method area	
pc: 04	constant pool
00 12 ldc	00 4303 4303
01 00 00	01 0000 0004
02 19 aload	02
03 00 00	03
04 12 ldc	04
05 01 01	05
06 2E iaload	06

stack	
optop: 02	local variables
00 4303 4303	00 002A 002A
01 002A 002A	01
02	02
03	03
04	04
05	05
06	06

heap	
4303 4303 "Compilers"	002A 002A [20,01,40,02,42]

Heap

method area	
pc: 06	constant pool
00 12 ldc	00 4303 4303
01 00 00	01 0000 0004
02 19 aload	02
03 00 00	03
04 12 ldc	04
05 01 01	05
06 2E iaload	06

stack	
optop: 03	local variables
00 4303 4303	00 002A 002A
01 002A 002A	01
02 0000 0004	02
03	03
04	04
05	05
06	06

heap	
4303 4303 "Compilers"	002A 002A [20,01,40,02,42]

Heap

method area	
pc: 07	constant pool
00 12 ldc	00 4303 4303
01 00 00	01 0000 0004
02 19 aload	02
03 00 00	03
04 12 ldc	04
05 01 01	05
06 2E iaload	06

stack	
optop: 02	local variables
00 4303 4303	00 002A 002A
01 0000 0042	01
02	02
03	03
04	04
05	05
06	06

heap	
4303 4303 "Compilers"	002A 002A [20,01,40,02,42]

JVM: Stack Frames

TU Delft

Static vs. Dynamic Dispatch

Dispatch

- link method call to method

Static dispatch

- type information at compile-time

Dynamic dispatch

- type information at run-time
- single dispatch: one parameter
- multiple dispatch: more parameters

Example: Static Call

```
function fac(n: int): int=
   if
      n = 0
   then
      1
   else
      n * fac(n - 1)
```

```
.class public Exp

   .method public static fac(I)I

            iload 1
            ifne else

            iconst_1
            ireturn

      else: iload 1
            dup
            iconst_1
            isub
            invokestatic Exp/fac(I)I
            imul
            ireturn
   .end method
```

Example: Dynamic Call

```
function fac(n: int): int=
   if
      n = 0
   then
      1
   else
      n * fac(n - 1)
```

```
.class public Exp

   .method public fac(I)I

            iload 1
            ifne else

            iconst_1
            ireturn

      else: iload 0
            iload 1
            dup
            iconst_1
            isub
            invokevirtual Exp/fac(I)I
            imul
            ireturn
   .end method
```

Code Pattern: Dynamic Method Call

Caller

- push object
- push parameters left-to-right
- call method

Virtual machine on call

- allocate space (frame data, operand stack, local variables)
- store frame data (data pointer, return address, exception table)
- store parameters as local variables
- dynamic dispatch
- point pc to method code

Code Pattern: Return from Method Call

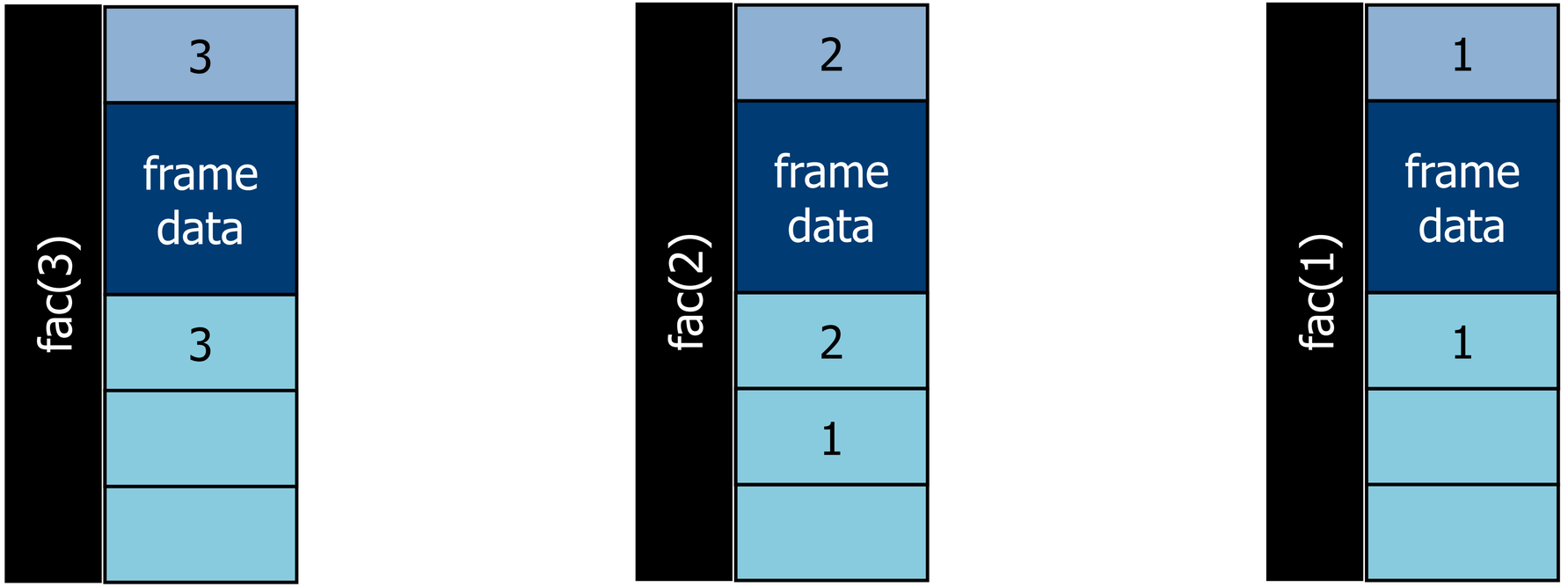
Callee

- parameters in local variables
- leave result on operand stack
- return to caller

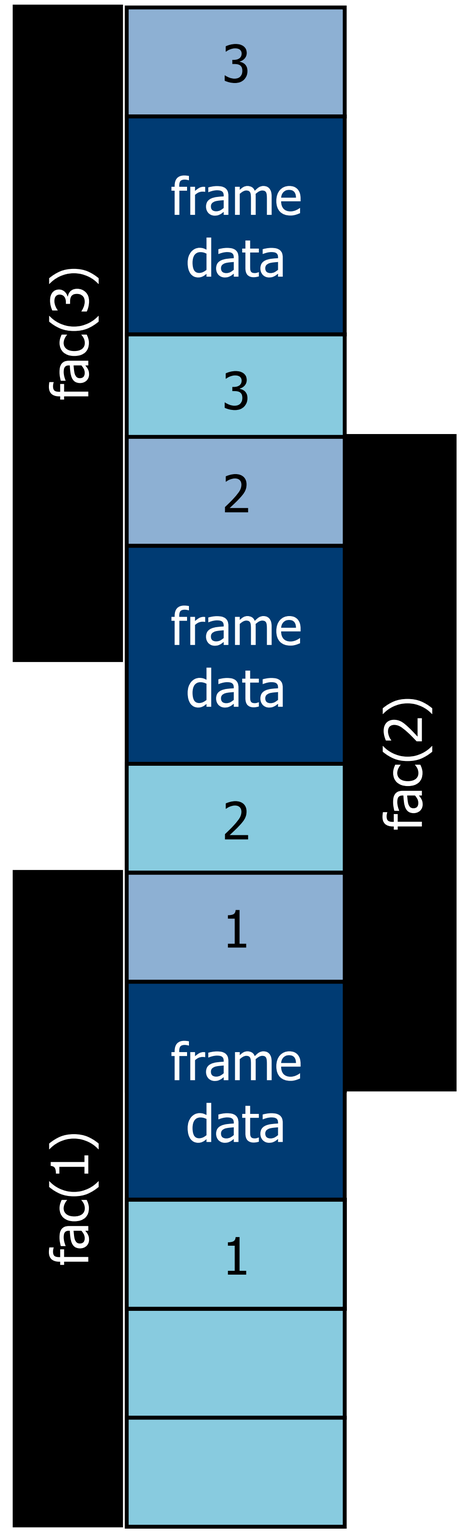
Virtual machine on return

- push result on caller's operand stack
- point pc to return address
- destroy frame

Implementation: Heap-Based



Implementation: Stack-Based



Stack Frames

method area

pc: 03

```
00    2A      aload_0
01    10      bipush
02    40
03    B6      invokevirtual
04    00
05    01      01
06    AC      ireturn
```

stack

optop: 02

00	4303	4303
01	0000	0040
02		
03		
04		
05		
06		

local variables

00	4303	4303
01		
02		
03		
04		
05		
06		

heap

Stack Frames

method area

pc: 80

80	2B	iload_1
81	59	dup
82	68	imul
83	AC	ireturn
84	00	
85	00	
86	00	

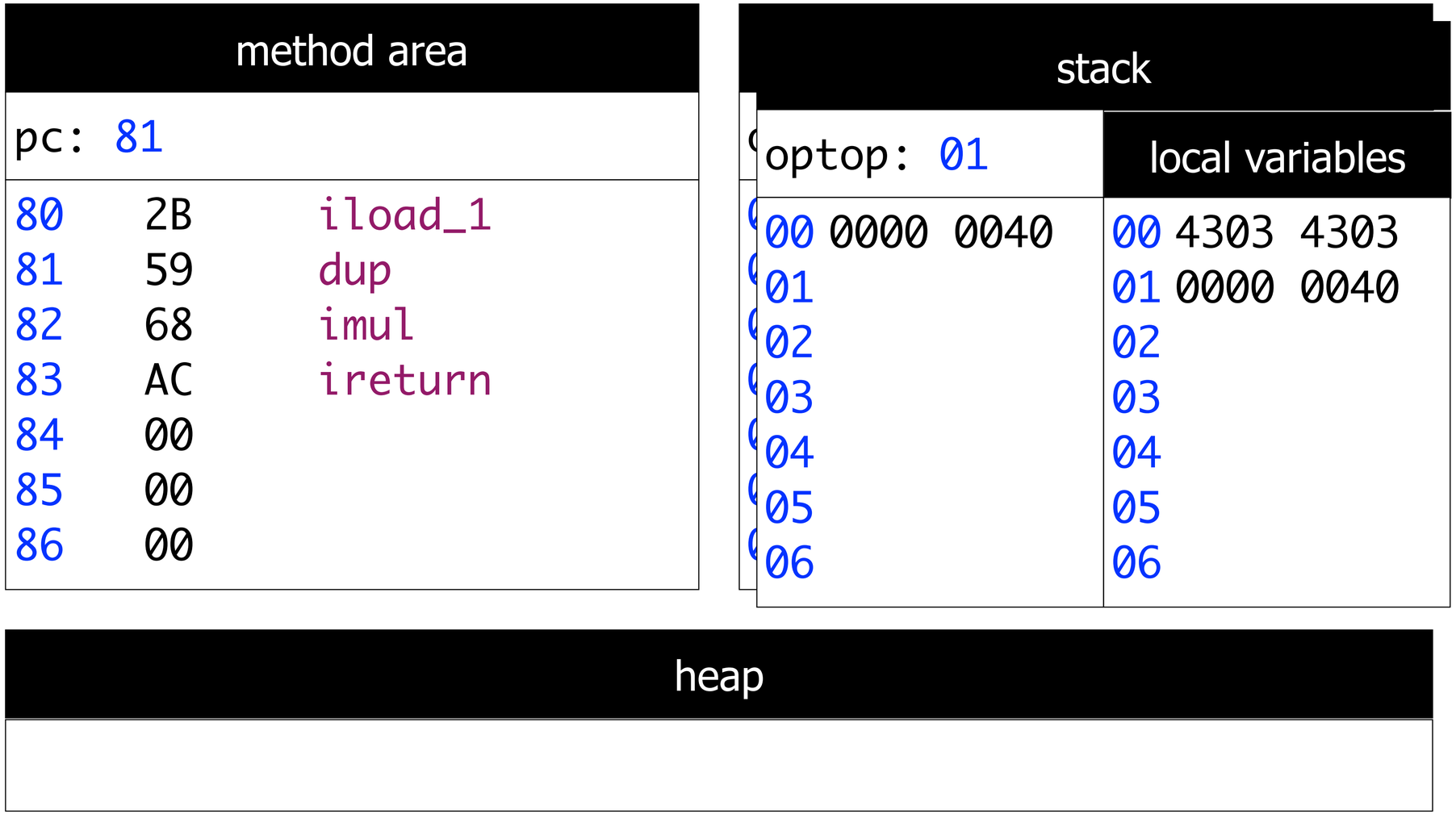
stack

optop: 00

	local variables
00	00 4303 4303
01	01 0000 0040
02	02
03	03
04	04
05	05
06	06

heap

Stack Frames



Stack Frames

method area

pc: 81

80	2B	iload_1
81	59	dup
82	68	imul
83	AC	ireturn
84	00	
85	00	
86	00	

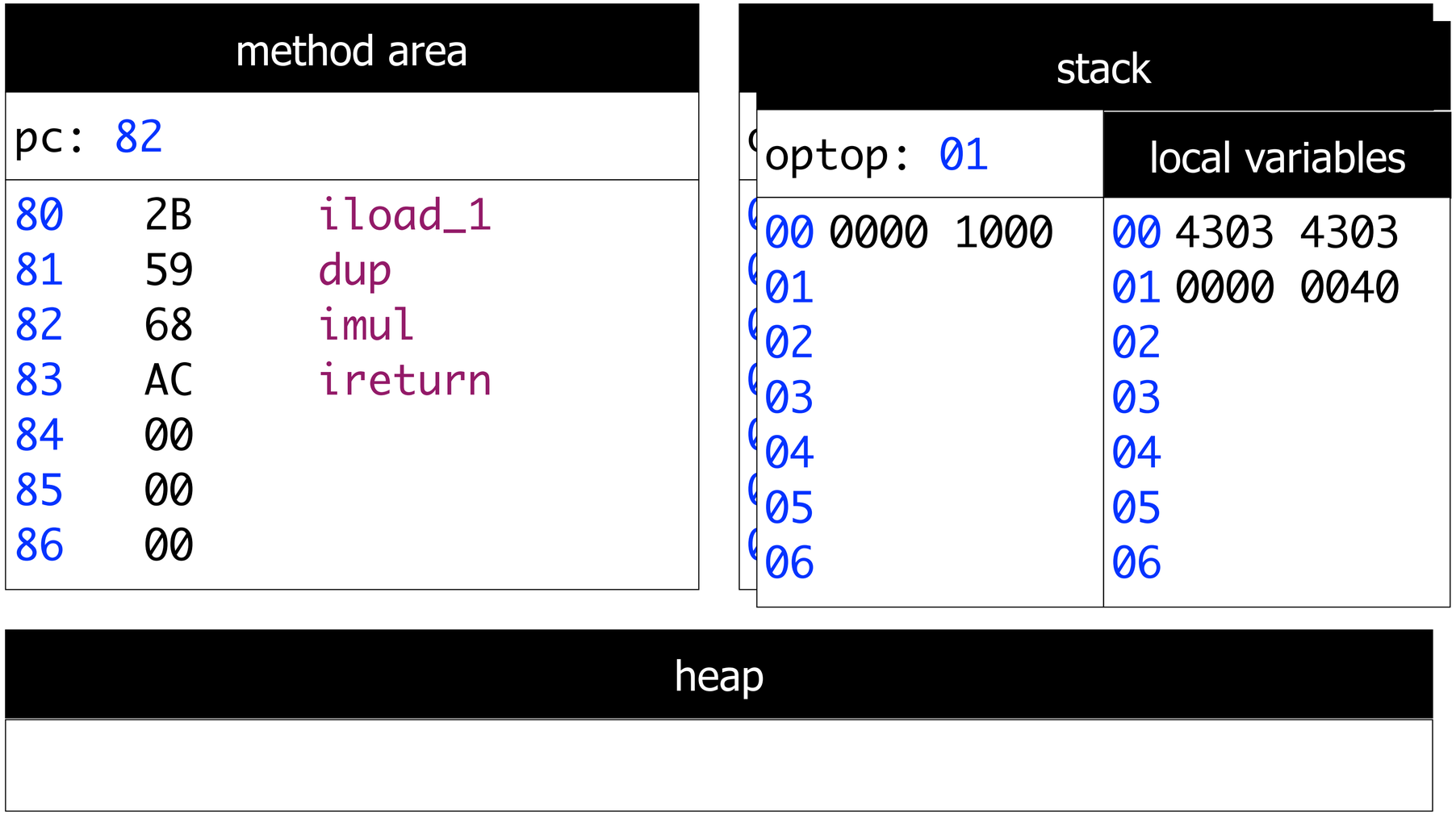
stack

optop: 02

	local variables
00 0000 0040	00 4303 4303
01 0000 0040	01 0000 0040
02	02
03	03
04	04
05	05
06	06

heap

Stack Frames



Stack Frames

method area

pc: 06

```
00    2A      aload_0
01    10      bipush
02    40
03    B6      invokevirtual
04    00
05    01      01
06    AC      ireturn
```

stack

optop: 01

00 0000 1000
01
02
03
04
05
06

local variables

00 4303 4303
01
02
03
04
05
06

heap

JVM: Class Files

Java Compiler

```
> ls

   Course.java

> javac -verbose Course.java

   [parsing started Course.java]
   [parsing completed 8ms]
   [loading java/lang/Object.class(java/lang:Object.class)]
   [checking university.Course]
   [wrote Course.class]
   [total 411ms]

> ls

   Course.class      Course.java
```

Class Files: Format

magic number `CAFEBABE`

class file version (minor, major)

constant pool count + constant pool

access flags

this class

super class

interfaces count + interfaces

fields count + fields

methods count + methods

attribute count + attributes

Jasmin Intermediate Language

```
.class public Exp

   .method public static fac(I)I

            iload 1
            ifne else

            iconst_1
            ireturn

      else: iload 1
            dup
            iconst_1
            isub
            invokestatic Exp/fac(I)I
            imul
            ireturn
   .end method
```

Optimization

Optimizations

Reasons

- code overhead
- execution overhead

Inlining

- replace calls by body of the procedure
- source code level

Tail recursion

- replace recursive calls by loops or jumps
- source or machine code level

Code Generation

```
function fac0(n0: int): int=
   if
      n0 = 0
   then
      1
   else
      n0 * fac0(n0 - 1)
```

```
.method public static fac0(I)I

            iload 1
            ldc 0
            if_icmpeq label0
            ldc 0
            goto label1
   label0:  ldc 1
   label1:  ifeq else0
            ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

           iload 1
           ldc 0
           if_icmpeq label0
           ldc 0
           goto label1
   label0: ldc 1
   label1: ifeq else0
           ldc 1
           goto end0
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

```
.method public static fac0(I)I

           iload_1
           ifne else0

           iconst_1
           ireturn

   else0:  iload_1
           dup
           iconst_1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
           ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

            iload 1
            ldc 0
            if_icmpeq label0
            ldc 0
            goto label1
   label0:  ldc 1
   label1:  ifeq else0
            ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

```
.method public static fac0(I)I

            iload 1
            ifeq label0
            ldc 0
            goto label1
   label0:  ldc 1
   label1:  ifeq else0
            ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

           iload 1
           ifeq label0
           ldc 0
           goto label1
   label0: ldc 1
   label1: ifeq else0
           ldc 1
           goto end0
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

```
.method public static fac0(I)I

           iload 1
           ifeq label0
           ldc 0
           ifeq else0
   label0: ldc 1
   label1: ifeq else0
           ldc 1
           goto end0
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

           iload 1
           ifeq label0
           ldc 0
           ifeq else0
   label0: ldc 1
   label1: ifeq else0
           ldc 1
           goto end0
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

```
.method public static fac0(I)I

           iload 1
           ifeq label0
           goto else0
   label0: ldc 1
   label1: ifeq else0
           ldc 1
           goto end0
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

          iload 1
          ifeq label0
          goto else0
   label0: ldc 1
   label1: ifeq else0
          ldc 1
          goto end0
   else0:  iload 1
          iload 1
          ldc 1
          isub
          invokestatic
             Exp/fac0(I)I
          imul
   end0:   ireturn
.end method
```

```
.method public static fac0(I)I

          iload 1
          ifeq label0
          goto else0
   label0: ldc 1
          ifeq else0
          ldc 1
          goto end0
   else0:  iload 1
          iload 1
          ldc 1
          isub
          invokestatic
             Exp/fac0(I)I
          imul
   end0:   ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

          iload 1
          ifeq label0
          goto else0
   label0: ldc 1
          ifeq else0
          ldc 1
          goto end0
   else0:  iload 1
          iload 1
          ldc 1
          isub
          invokestatic
             Exp/fac0(I)I
          imul
   end0:   ireturn
.end method
```

```
.method public static fac0(I)I

          iload 1
          ifeq label0
          goto else0
   label0: ldc 1
          goto end0
   else0:  iload 1
          iload 1
          ldc 1
          isub
          invokestatic
             Exp/fac0(I)I
          imul
   end0:   ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

            iload 1
            ifeq label0
            goto else0
   label0:  ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

```
.method public static fac0(I)I

            iload 1
            ifneq else0
   label0:  ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

            iload 1
            ifneq else0
   label0:  ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

```
.method public static fac0(I)I

            iload 1
            ifneq else0
            ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

           iload 1
           ifneq else0
           ldc 1
           goto end0
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

```
.method public static fac0(I)I

           iload 1
           ifneq else0
           ldc 1
           ireturn
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

           iload 1
           ifneq else0
           ldc 1
           ireturn
   else0:  iload 1
           iload 1
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

```
.method public static fac0(I)I

           iload 1
           ifneq else0
           ldc 1
           ireturn
   else0:  iload 1
           dup
           ldc 1
           isub
           invokestatic
              Exp/fac0(I)I
           imul
   end0:   ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

            iload 1
            ifneq else0
            ldc 1
            ireturn
   else0:   iload 1
            dup
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

```
.method public static fac0(I)I

            iload_1
            ifneq else0
            ldc 1
            ireturn
   else0:   iload_1
            dup
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

Optimization

```
.method public static fac0(I)I

            iload_1
            ifneq else0
            ldc 1
            ireturn
   else0:   iload_1
            dup
            ldc 1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

```
.method public static fac0(I)I

            iload_1
            ifneq else0
            iconst_1
            ireturn
   else0:   iload_1
            dup
            iconst_1
            isub
            invokestatic
               Exp/fac0(I)I
            imul
   end0:    ireturn
.end method
```

Tail Recursion Elimination

Example: Tail Recursion

```
.class public Exp

   .method public static fac(I)I

            iload 1
            ifne else

            iconst_1
            ireturn

      else: iload 1
            dup
            iconst_1
            isub
            invokestatic Exp/fac(I)I
            imul
            ireturn
   .end method
```

Example: Tail Recursion

```
.class public Exp

   .method public static fac(I)I

            iload 1
            ifne else

            iconst_1
            ireturn

      else: iload 1
            dup
            iconst_1
            isub
            invokestatic Exp/fac(I)I
            imul
            ireturn
   .end method
```

```
.class public Exp

   .method public static fac(II)I

            iload 1
            ifne else

            iload 2
            ireturn

      else: iload 1
            iconst_1
            isub
            iload 1
            iload 2
            imul
            invokestatic Exp/fac(II)I
            ireturn
   .end method
```

Example: Tail Recursion

```
.class public Exp

   .method public static fac(II)I

            iload 1
            ifne else

            iload 2
            ireturn

      else: iload 1
            iconst_1
            isub
            iload 1
            iload 2
            imul
            invokestatic Exp/fac(II)I
            ireturn
   .end method
```

```
.class public Exp

   .method public static fac(II)I

      strt: iload 1
            ifne else

            iload 2
            ireturn

      else: iload 1
            iconst_1
            isub
            iload 1
            iload 2
            imul
            istore 2
            istore 1
            goto strt
```

Code Generation: Strings

Printing Strings

```
to-jbc = ?Nil()   ; <printstring> "aconst_null\n"
to-jbc = ?NoVal() ; <printstring> "nop\n"
to-jbc = ?Seq(es) ; <list-loop(to-jbc)> es

to-jbc =
   ?Int(i);
   <printstring> "ldc ";
   <printstring> i;
   <printstring> "\n"

to-jbc = ?Bop(op, e1, e2) ; <to-jbc> e1 ; <to-jbc> e2 ; <to-jbc> op

to-jbc = ?PLUS()  ; <printstring> "iadd\n"
to-jbc = ?MINUS() ; <printstring> "isub\n"
to-jbc = ?MUL()   ; <printstring> "imul\n"
to-jbc = ?DIV()   ; <printstring> "idiv\n"
```

String Concatenation

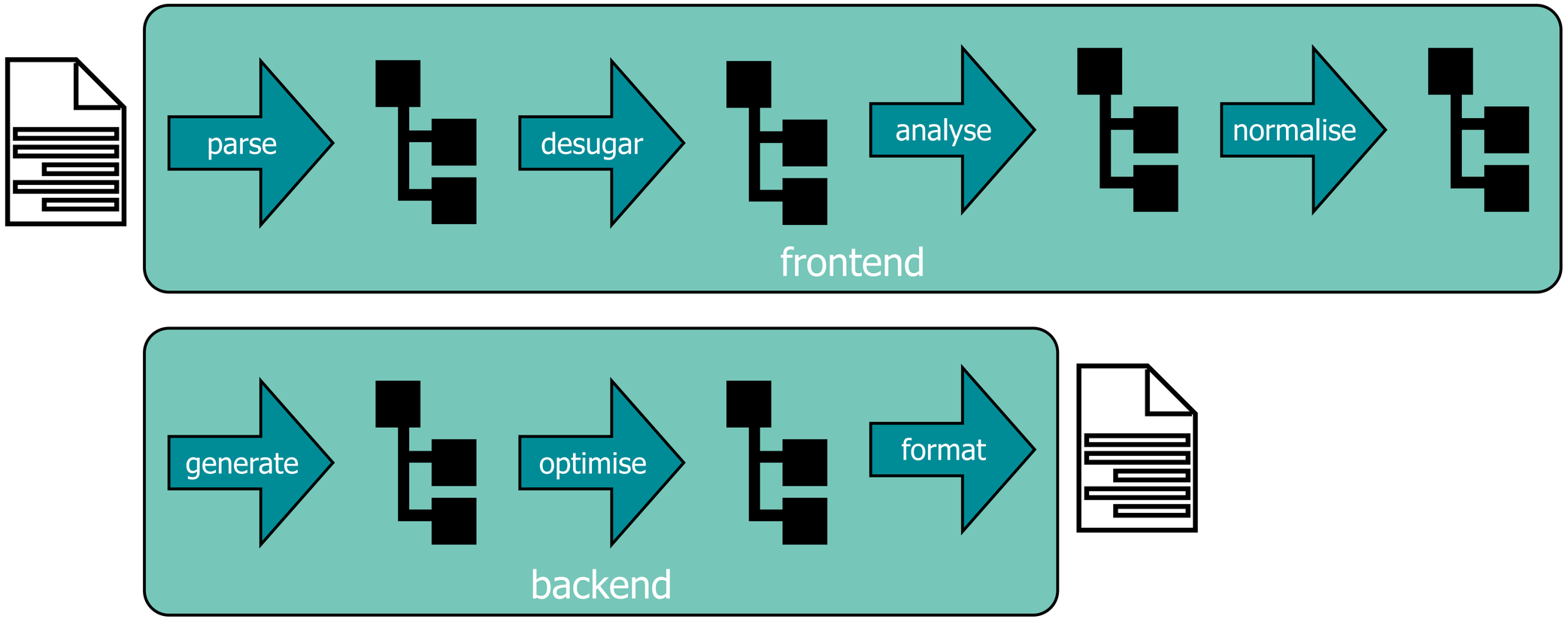
```
to-jbc: Nil()   -> "aconst_null\n"
to-jbc: NoVal() -> "nop\n"
to-jbc: Seq(es) -> <concat-strings> <map(to-jbc)> es

to-jbc: Int(i) -> <concat-strings> ["ldc ", i, "\n"]

to-jbc: Bop(op, e1, e2) -> <concat-strings> [ <to-jbc> e1,
                                              <to-jbc> e2,
                                              <to-jbc> op ]

to-jbc: PLUS()  -> "iadd\n"
to-jbc: MINUS() -> "isub\n"
to-jbc: MUL()   -> "imul\n"
to-jbc: DIV()   -> "idiv\n"
```

String Interpolation

```
to-jbc: Nil()   -> $[aconst_null]
to-jbc: NoVal() -> $[nop]
to-jbc: Seq(es) -> <map-to-jbc> es

map-to-jbc: [] -> $[]
map-to-jbc: [h|t] ->
   $[[<to-jbc> h]
     [<map-to-jbc> t]]

to-jbc: Int(i) -> $[ldc [i]]
to-jbc: Bop(op, e1, e2) ->
 $[[<to-jbc> e1]
   [<to-jbc> e2]
   [<to-jbc> op]]

to-jbc: PLUS()  -> $[iadd]
to-jbc: MINUS() -> $[isub]
to-jbc: MUL()   -> $[imul]
to-jbc: DIV()   -> $[idiv]
```

Code Generation: Transformation

Compilation by Transformation



Transformation

```
to-jbc: Nil()   -> [ ACONST_NULL() ]
to-jbc: NoVal() -> [ NOP() ]
to-jbc: Seq(es) -> <mapconcat(to-jbc)> es

to-jbc: Int(i)    -> [ LDC(Int(i)) ]
to-jbc: String(s) -> [ LDC(String(s)) ]

to-jbc: Bop(op, e1, e2) -> <mapconcat(to-jbc)> [ e1, e2, op ]

to-jbc: PLUS()  -> [ IADD() ]
to-jbc: MINUS() -> [ ISUB() ]
to-jbc: MUL()   -> [ IMUL() ]
to-jbc: DIV()   -> [ IDIV() ]

to-jbc: Assign(lhs, e) -> <concat> [ <to-jbc> e, <lhs-to-jbc> lhs ]

to-jbc:     Var(x) -> [ ILOAD(x) ]  where <type-of> Var(x) => INT()
to-jbc:     Var(x) -> [ ALOAD(x) ]  where <type-of> Var(x) => STRING()
lhs-to-jbc: Var(x) -> [ ISTORE(x) ] where <type-of> Var(x) => INT()
lhs-to-jbc: Var(x) -> [ ASTORE(x) ] where <type-of> Var(x) => STRING()
```

Transformation

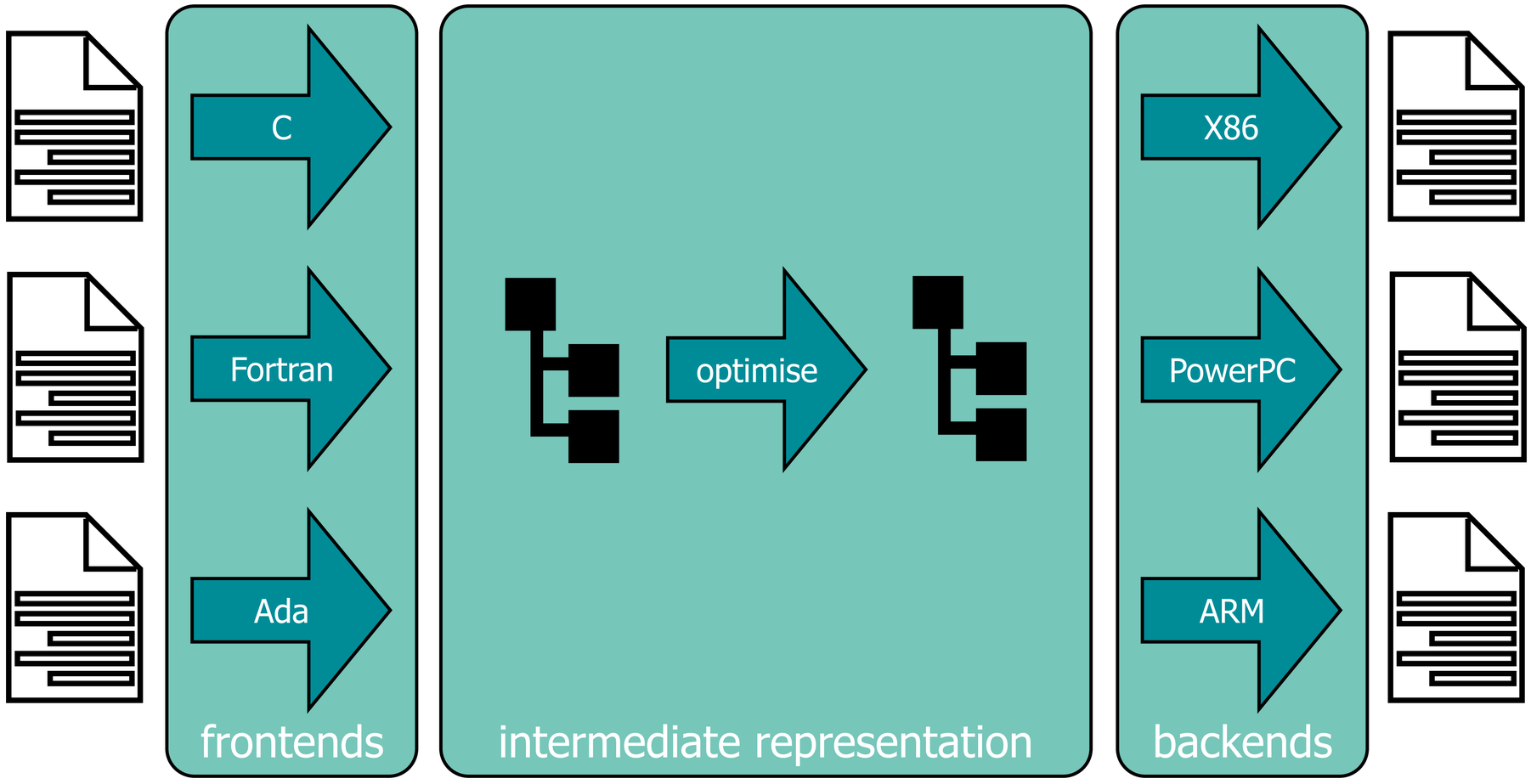
```
to-jbc:
   IfThenElse(e1, e2, e3) -> <concat>   [ <to-jbc> e1
                              , [ IFEQ(LabelRef(else)) ]
                              , <to-jbc> e2
                              , [ GOTO(LabelRef(end)), Label(else) ]
                              , <to-jbc> e3
                              , [ Label(end) ]
                              ]
   where <newname> "else" => else
   where <newname> "end"  => end

to-jbc:
   While(e1, e2) -> <concat>[ [ GOTO(LabelRef(check)), Label(body) ]
                            , <to-jbc> e2
                            , [ Label(check) ]
                            , <to-jbc> e1
                            , [ IFNE(LabelRef(body)) ]
                            ]
   where <newname> "test" => check
   where <newname> "body" => body
```

Transformation: Example

```
function fac(n: int): int=
   if
      n = 0
   then
      1
   else
      n * fac(n - 1)
```

```
.method public static fac(I)I

            iload 1
            ldc 0
            if_icmpeq label0
            ldc 0
            goto label1
   label0:  ldc 1
   label1:  ifeq else0
            ldc 1
            goto end0
   else0:   iload 1
            iload 1
            ldc 1
            isub
            invokestatic Exp/fac(I)I
            imul
   end0:    ireturn
.end method
```

Compiler Infrastructure: LLVM



Next

Next

Back-End

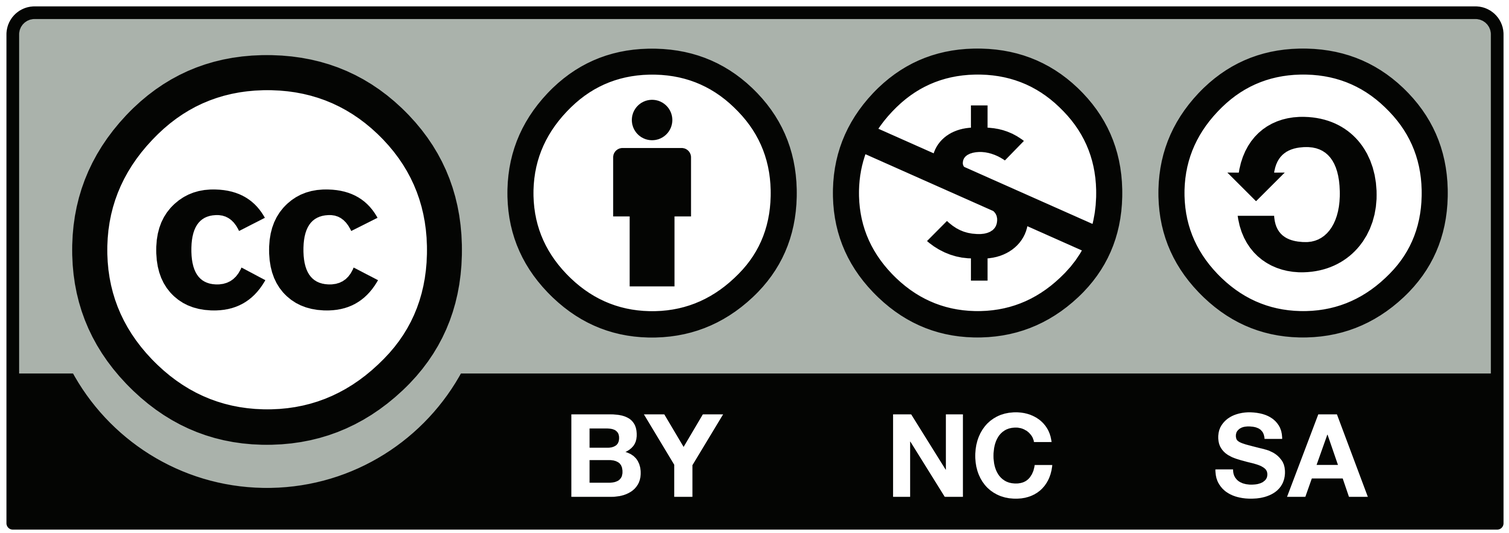
- Lecture 11: Dataflow Analysis (Nov 28)
- Lecture 12: Garbage Collection (Dec 5)
- Lecture 13: Just-in-Time Compilation (Interpreters & Partial Evaluation) (Dec 12)

Parsing

- Lecture 14: LL Parsing (Dec 19)
- Lecture 15: LR Parsing (Jan 9)

Lab

- Lab 6: Testing Type Analysis (Nov 22)
- Lab 7: Type Analyis (Dec 6)
- Lab 8: Compiling Minimal Programs (Dec 13)
- Lab 9: Compiling Expressions and Statements (Dec 22)
- Lab 10: Compiling Fields, Parameters, and Variables (Jan 19)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