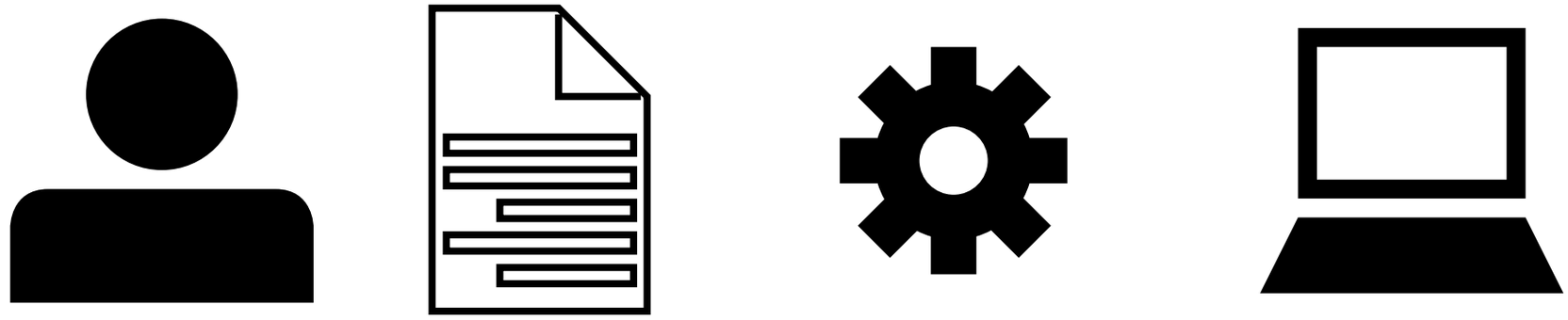
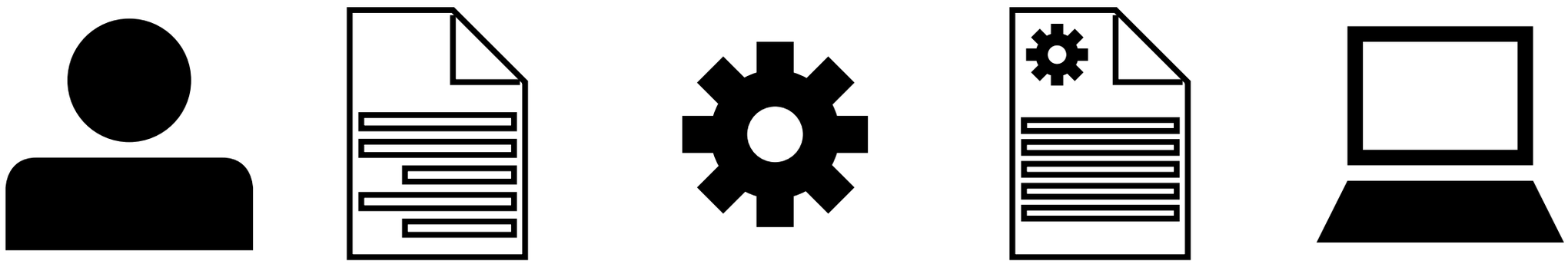
Programming Languages

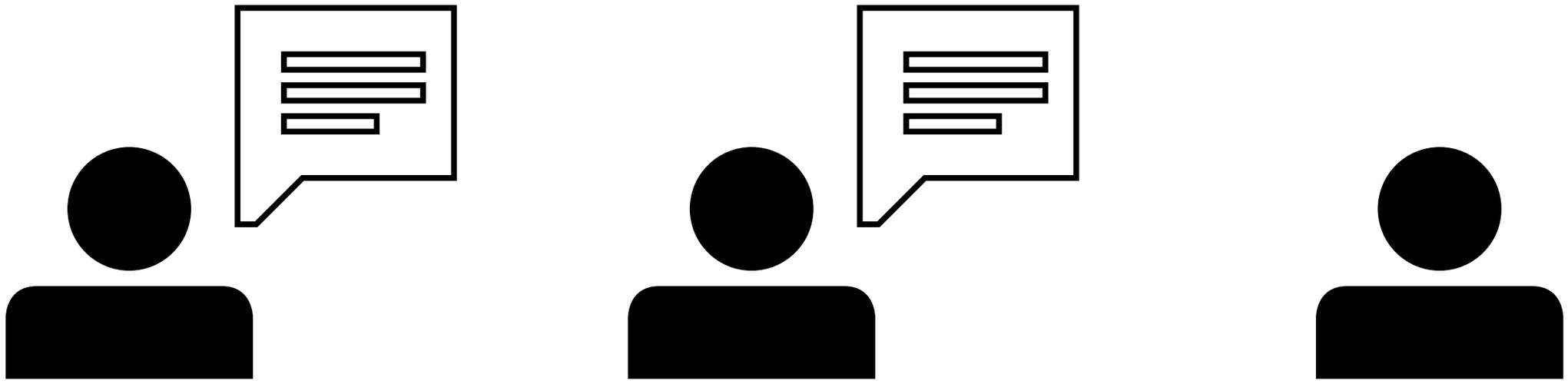
imperative & object-oriented

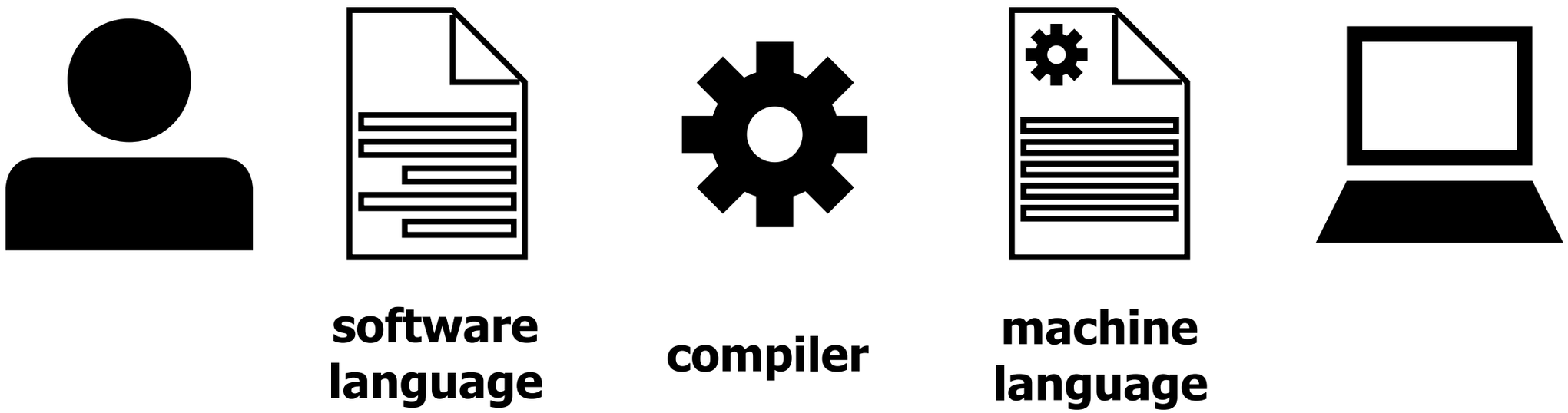
Guido Wachsmuth, Eelco Visser


BIGGER PICTU


software
language
interpreter

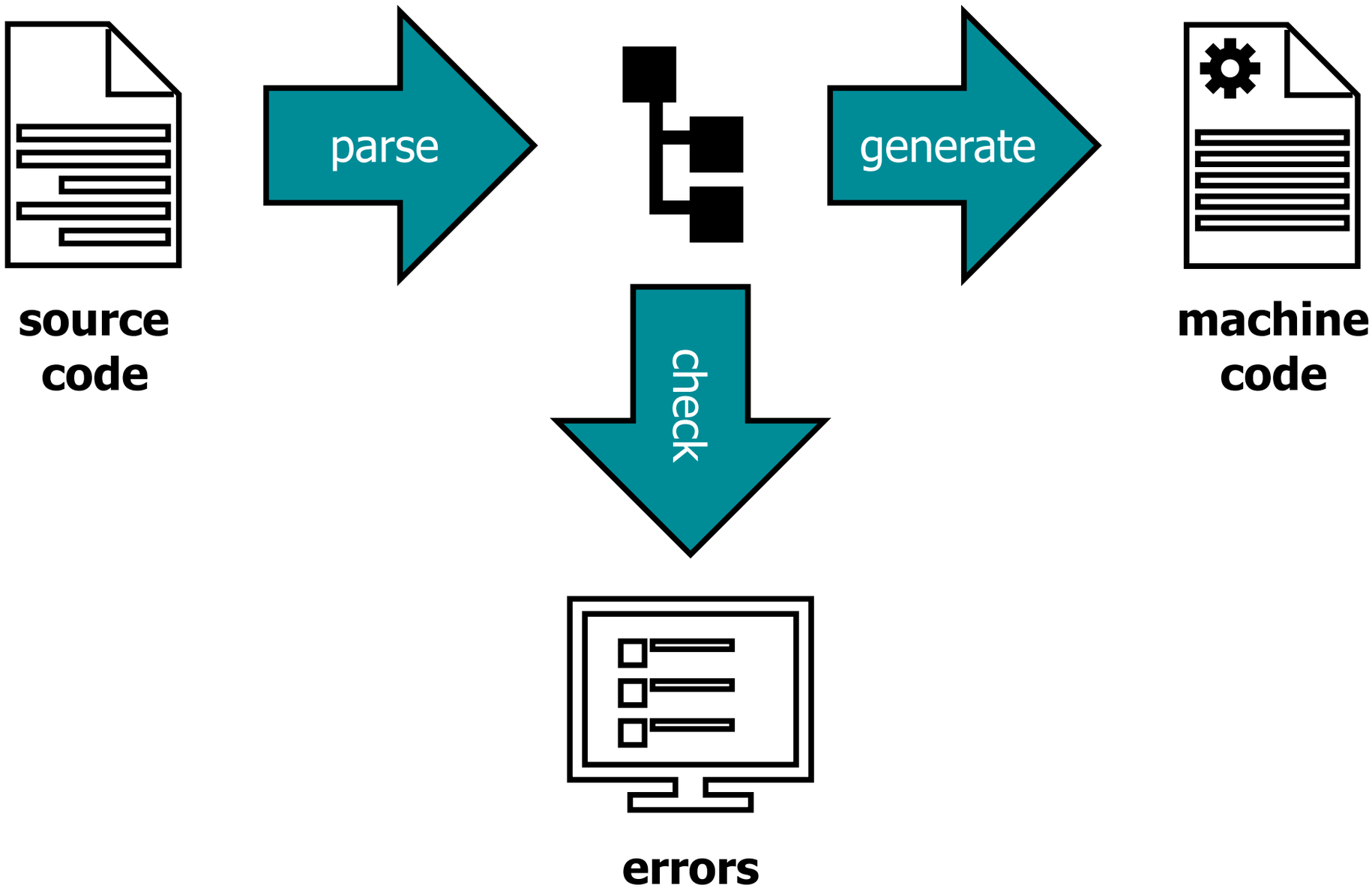

software
language
compiler
machine
language


natural language
translator
natural language


software language
compiler
machine language

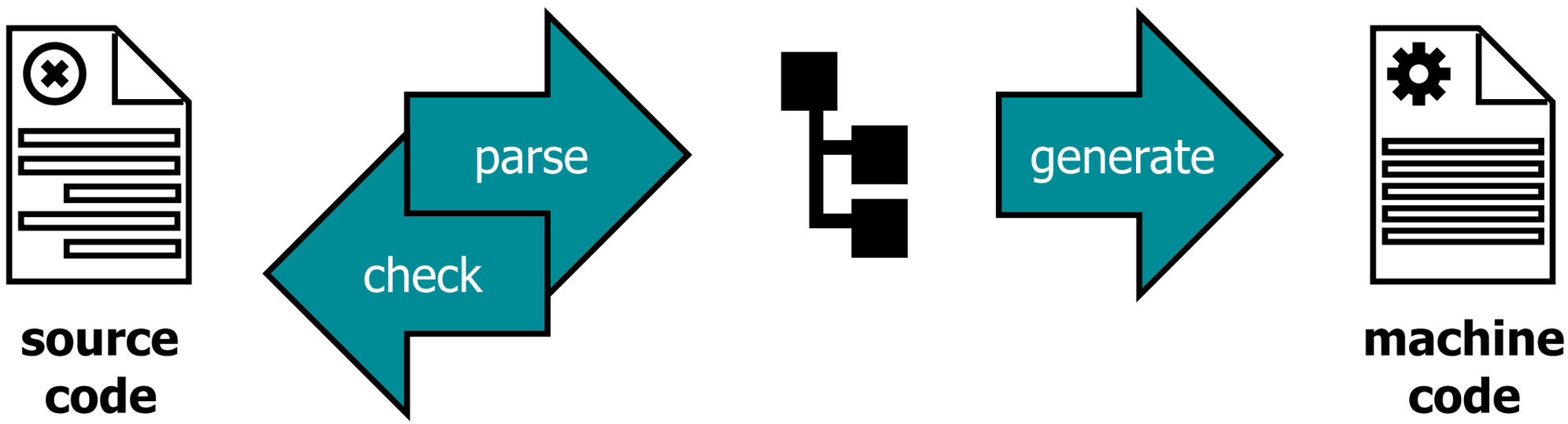
Traditional compilers

architecture



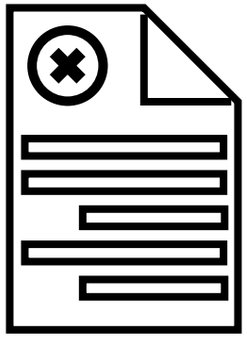
Modern compilers in IDEs

architecture

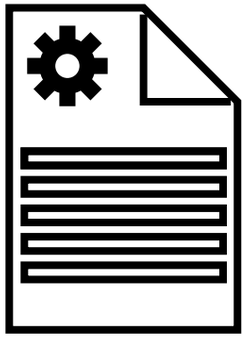


Compilers are inverted abstractions

architecture



source code



machine code

Compilers Invert Abstractions

Computers speak machine language

- basic instructions to move around and combine small things

Humans do not speak machine language very well

- “mov; loadi; jump” anyone?

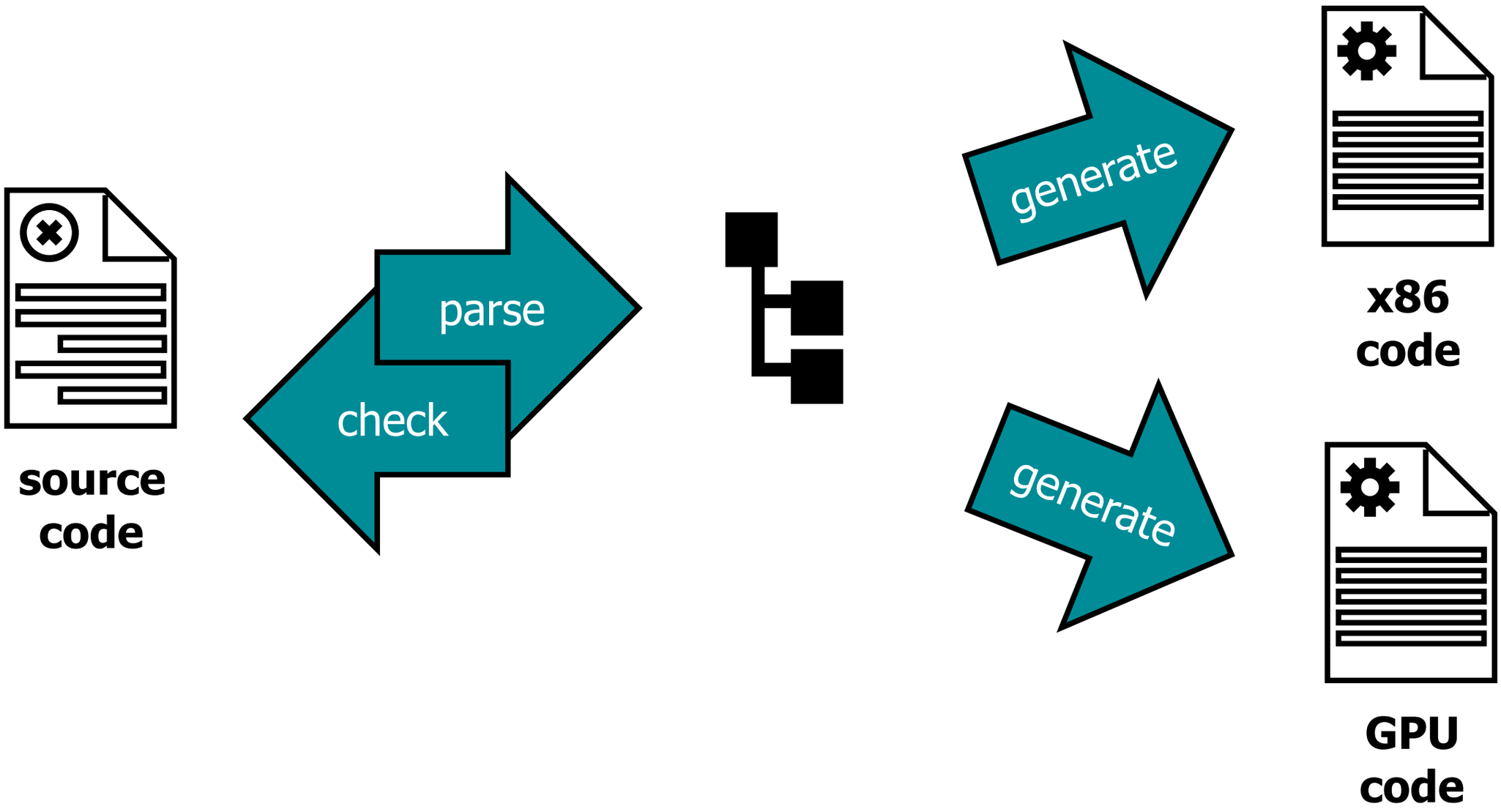
Programming languages abstract from machine language

- capture common programming patterns in language constructs
- abstract from uninteresting variation in machines

Compilers invert the abstractions of programming languages

Portability: Platform Independence

architecture



Understanding Compilers Requires …

Understanding machine languages

- machine architecture, instruction sets

Understanding programming language (abstraction)s

- memory, control-flow, procedures, modules, …
- safety mechanisms: type systems & other static analyses

Understanding how to define mapping from PL to ML

- semantics of such mappings
- techniques to implement such mappings

Imperative Languages

state & statements

procedures

types

Object-Oriented Languages

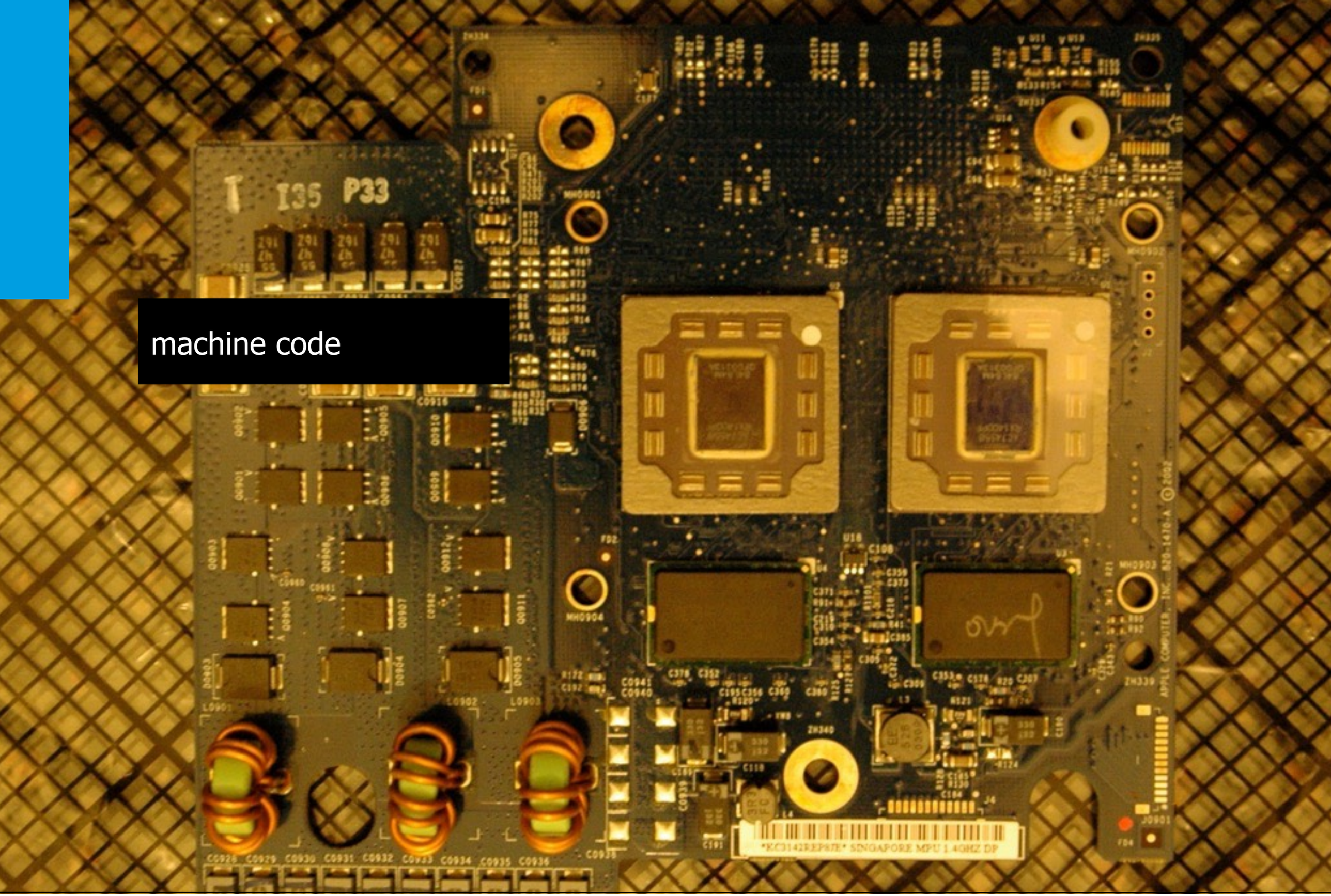
objects & messages

types

Imperative Languages

state & statements

machine code



State

basic concepts

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, …)

x86 family
registers

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

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special purpose registers

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

Example: x86 Assembler

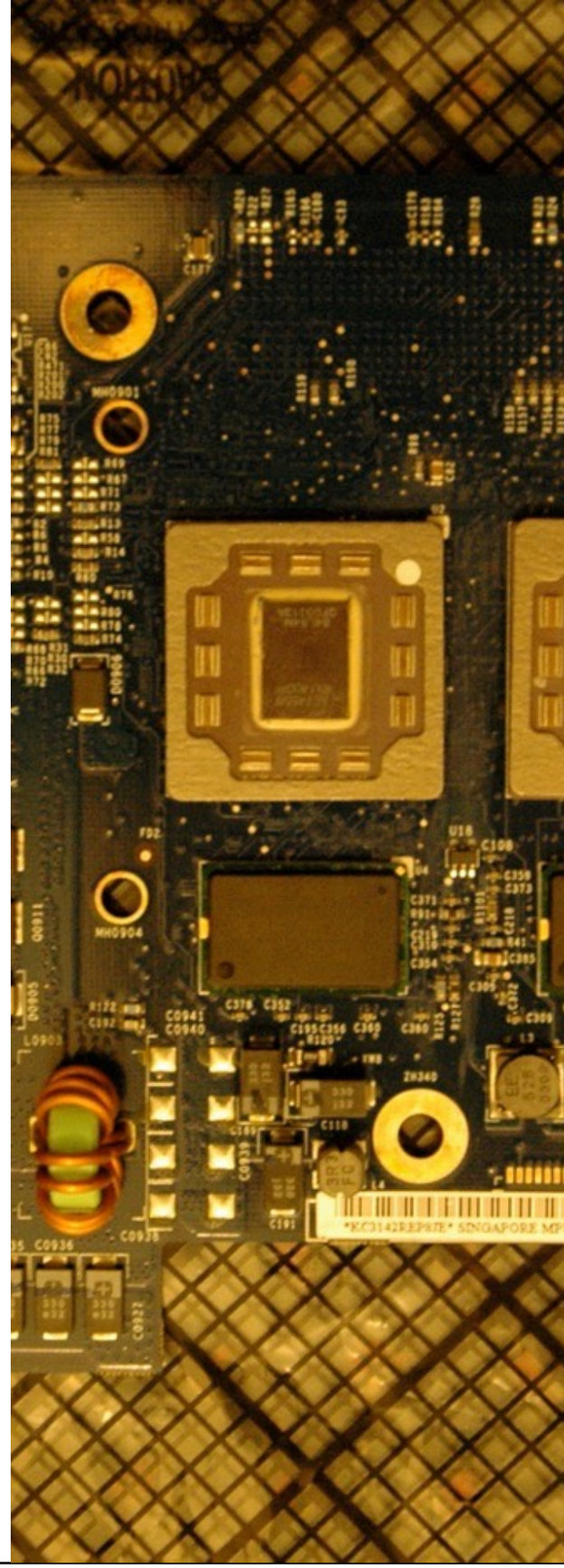
basic concepts

```
    mov AX [1]

    mov CX AX

L:  dec CX
    mul CX
    cmp CX 1
    ja  L

    mov [2] AX
```



Example: x86 Assembler

basic concepts

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    mov AX [1]          read memory

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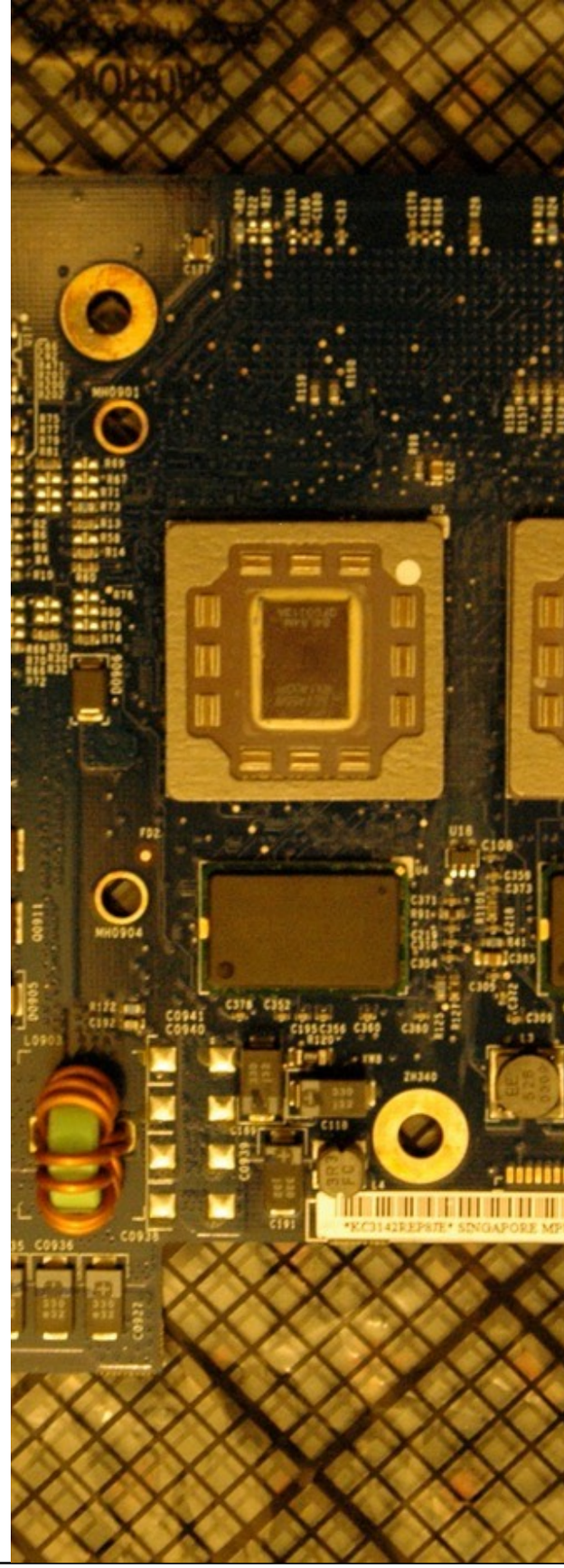

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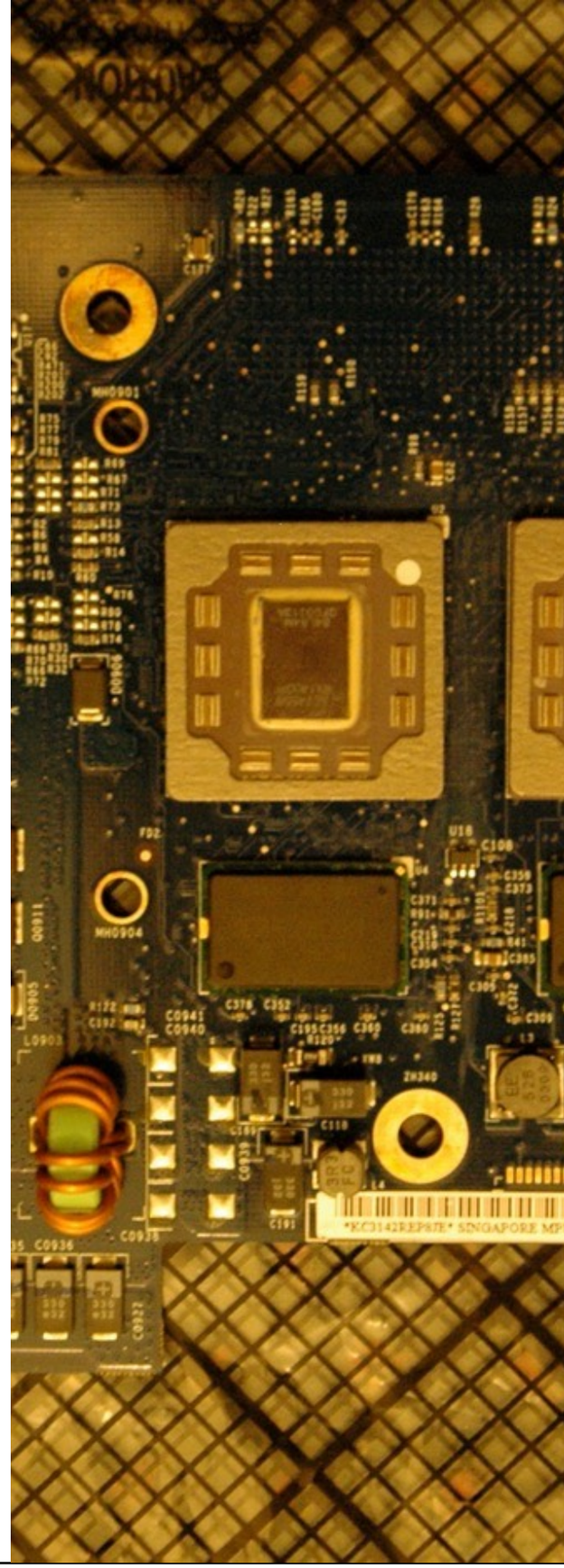

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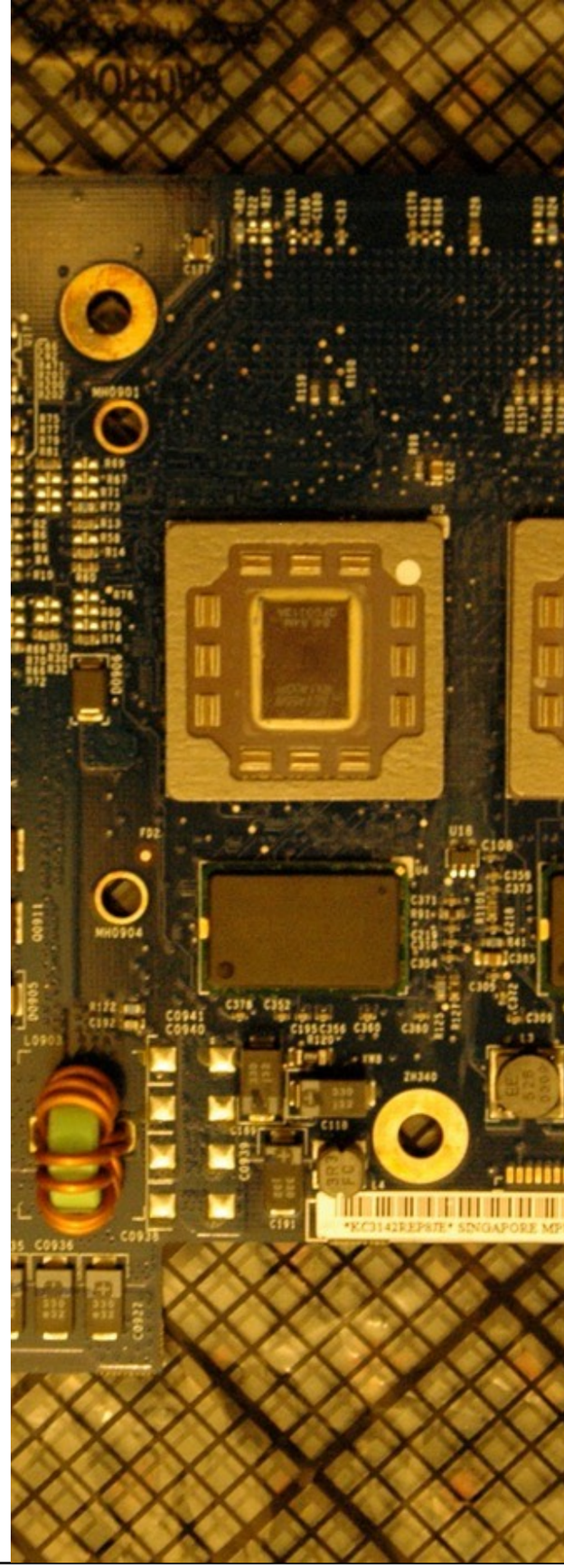

Example: x86 Assembler

basic concepts

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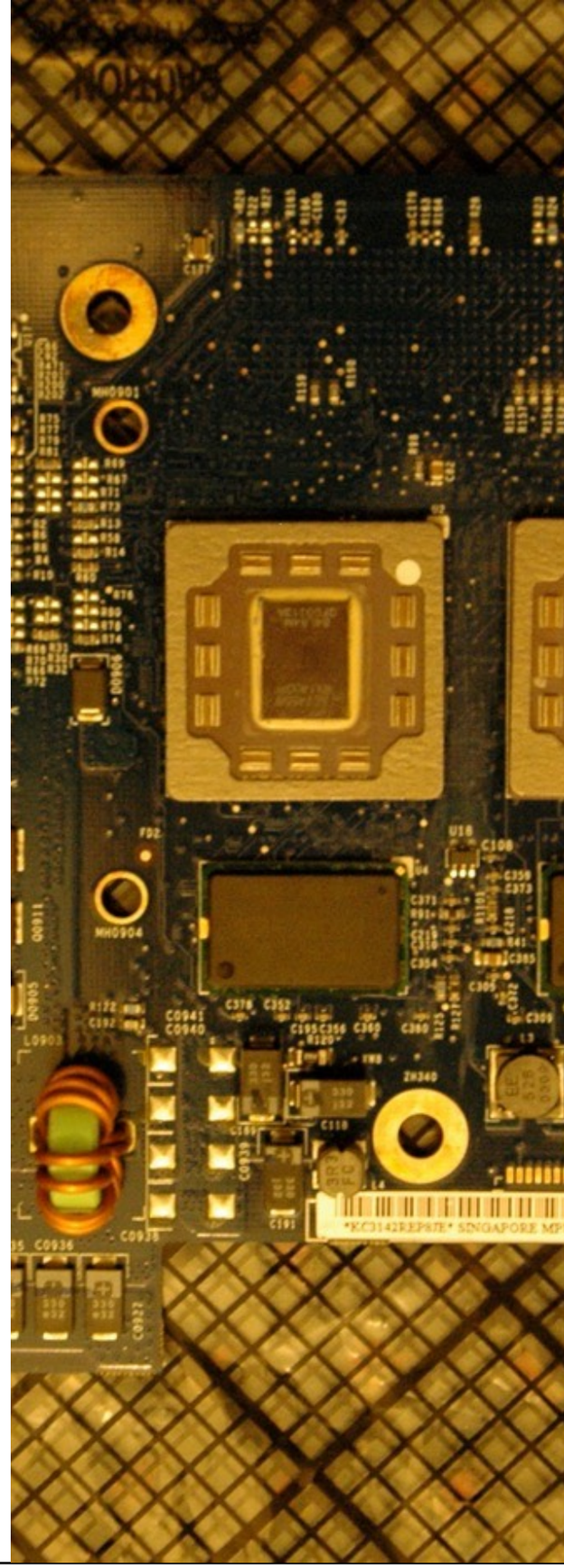

Example: Java Bytecode

basic concepts

```
.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
```

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basic concepts

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read memory

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read memory

calculation

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```

jump

read memory

calculation

Memory & Control Abstractions

basic concepts

Memory abstractions

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

Control-flow abstractions

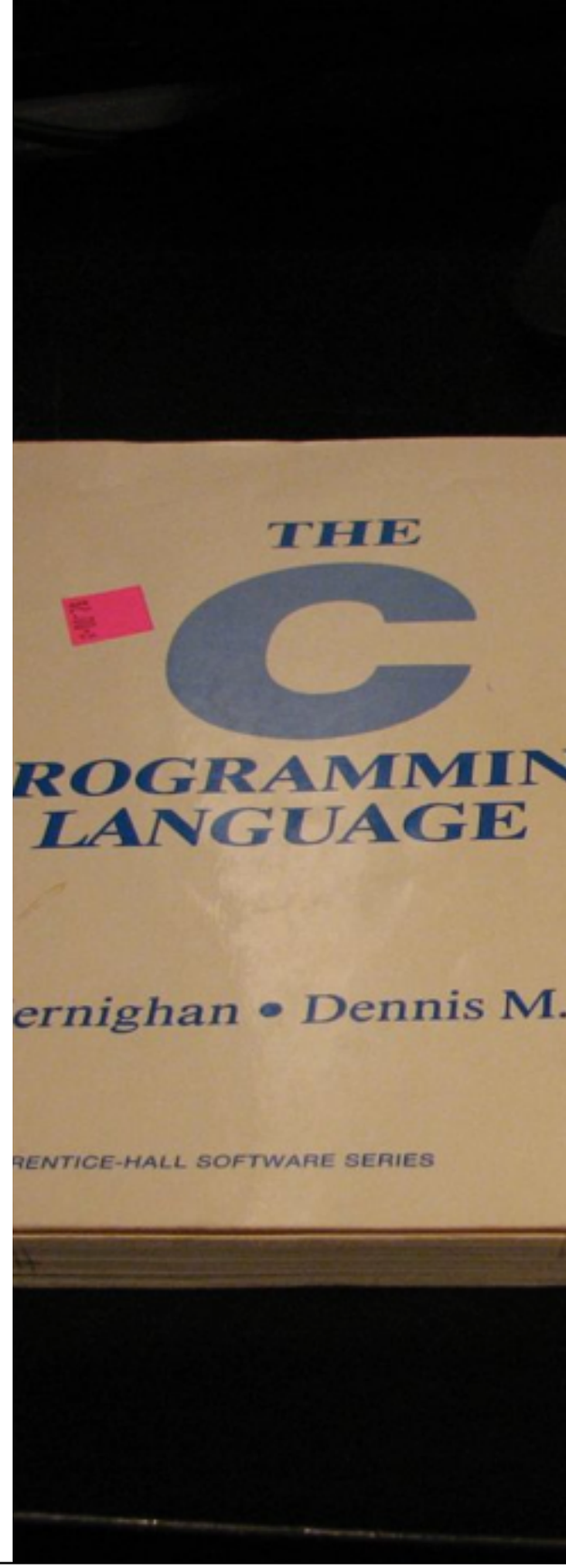
- structured control-flow: abstract over unstructured jumps
- ‘go to statement considered harmful’ Edgser Dijkstra, 1968

Example: C

states & statements

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

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



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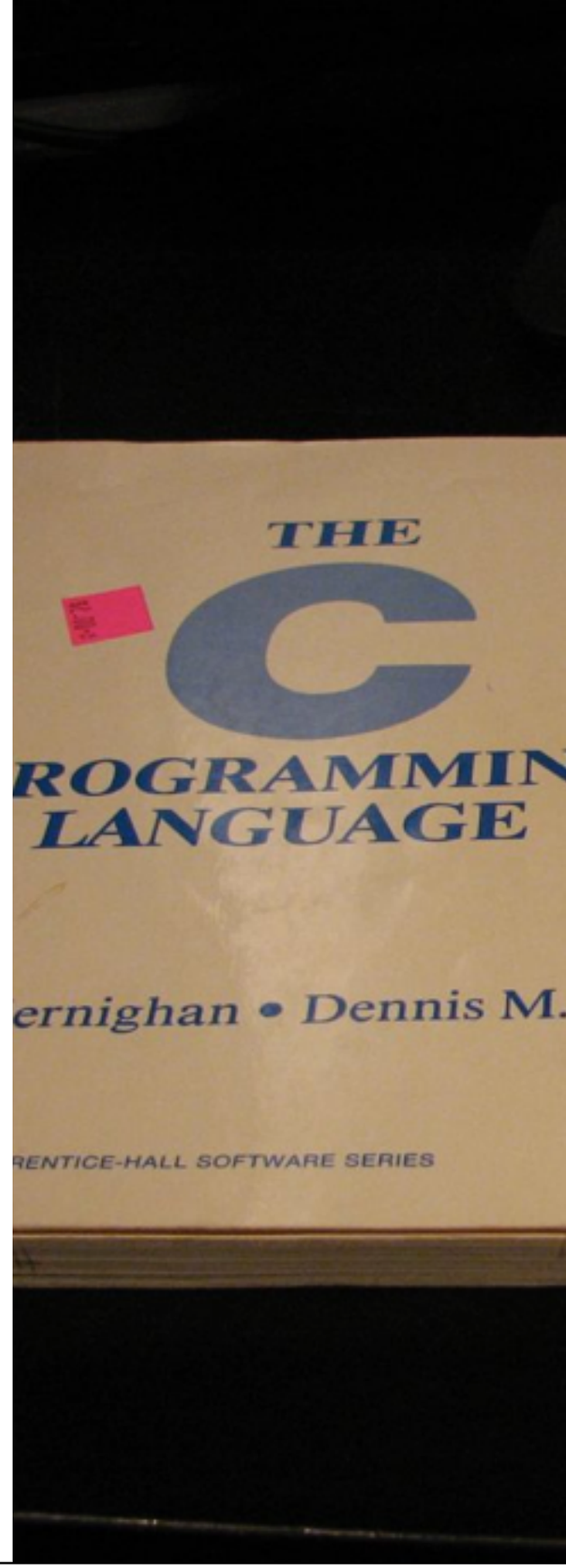
variable



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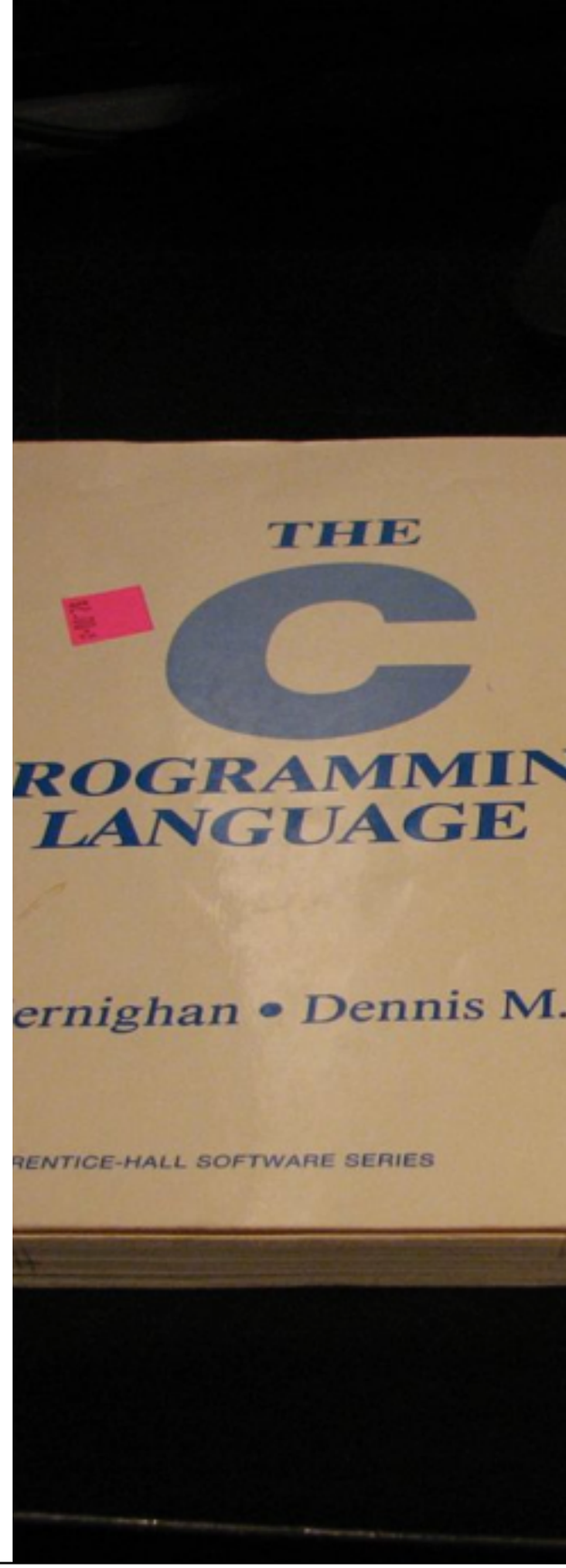
variable

expression



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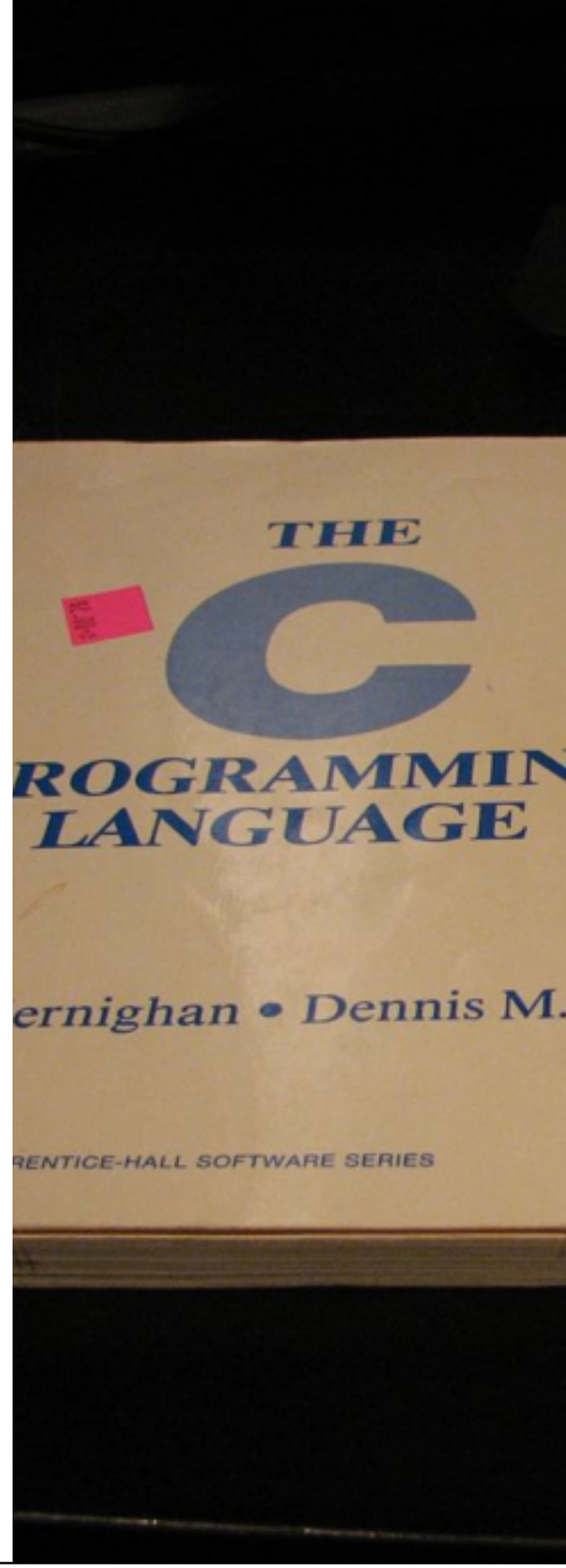
variable

expression

assignment

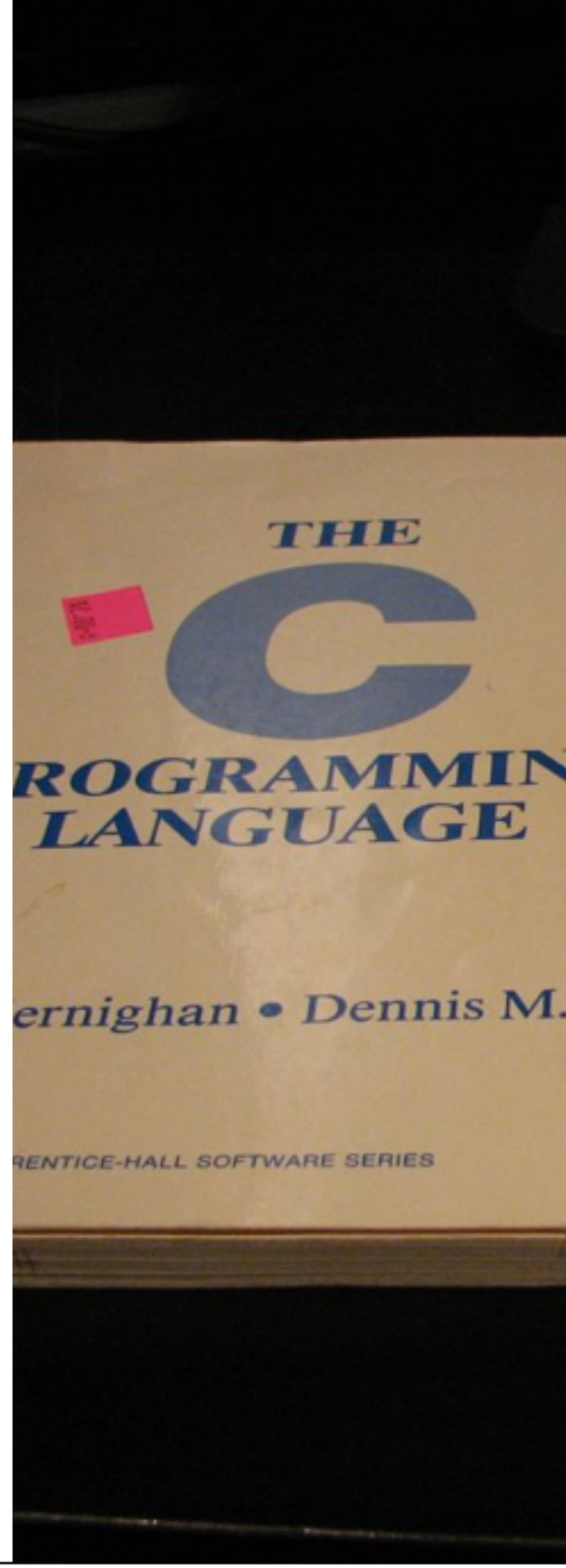


Example: C

states & statements

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

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



Example: Tiger

states & statements

```
/* 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
```

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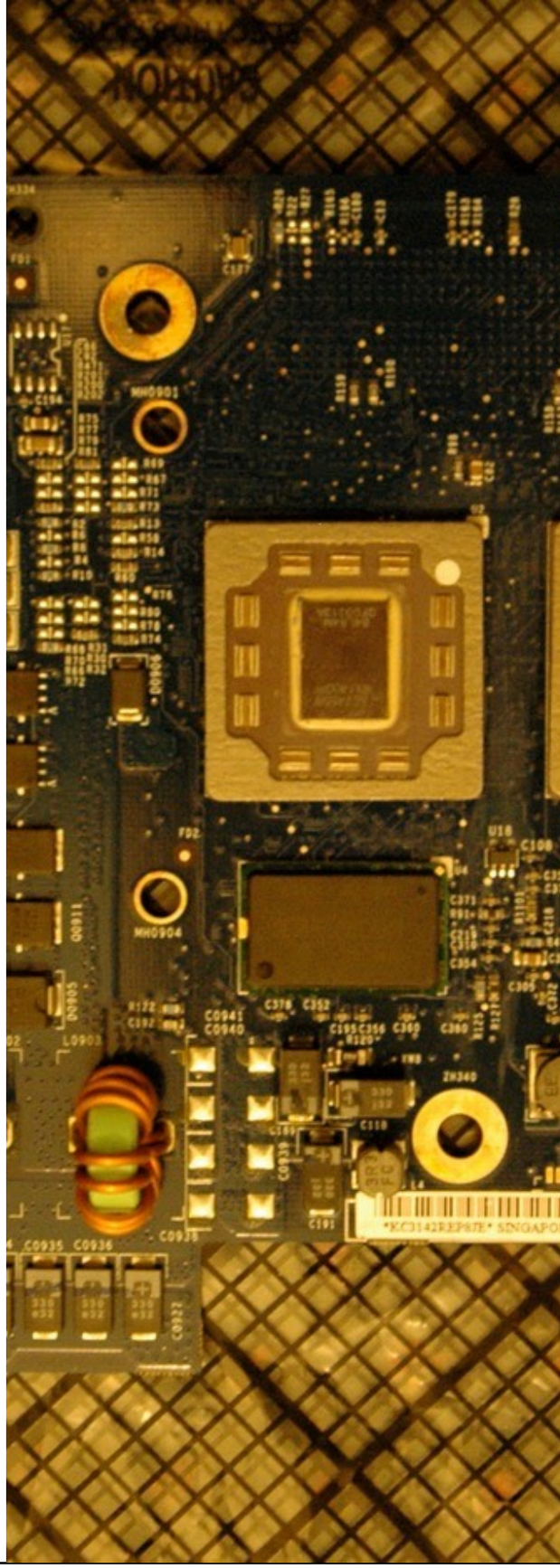
Imperative Languages

procedures

Example: x86 Assembler
modularity

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

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



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pass parameter

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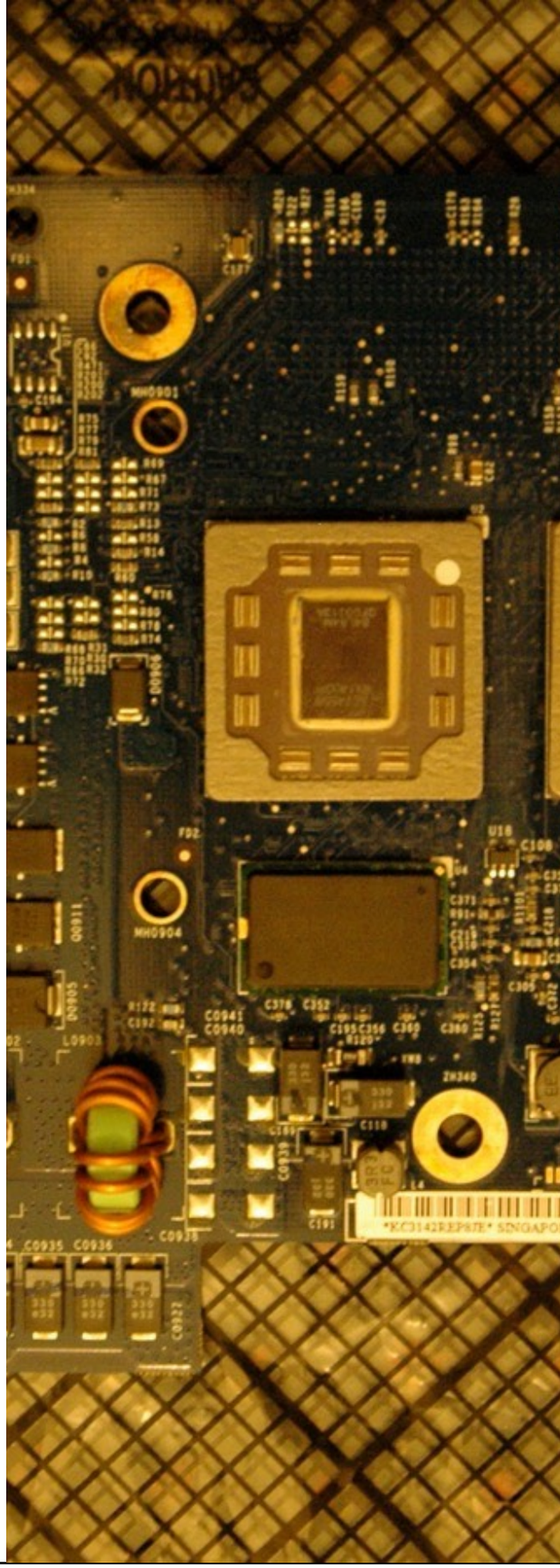

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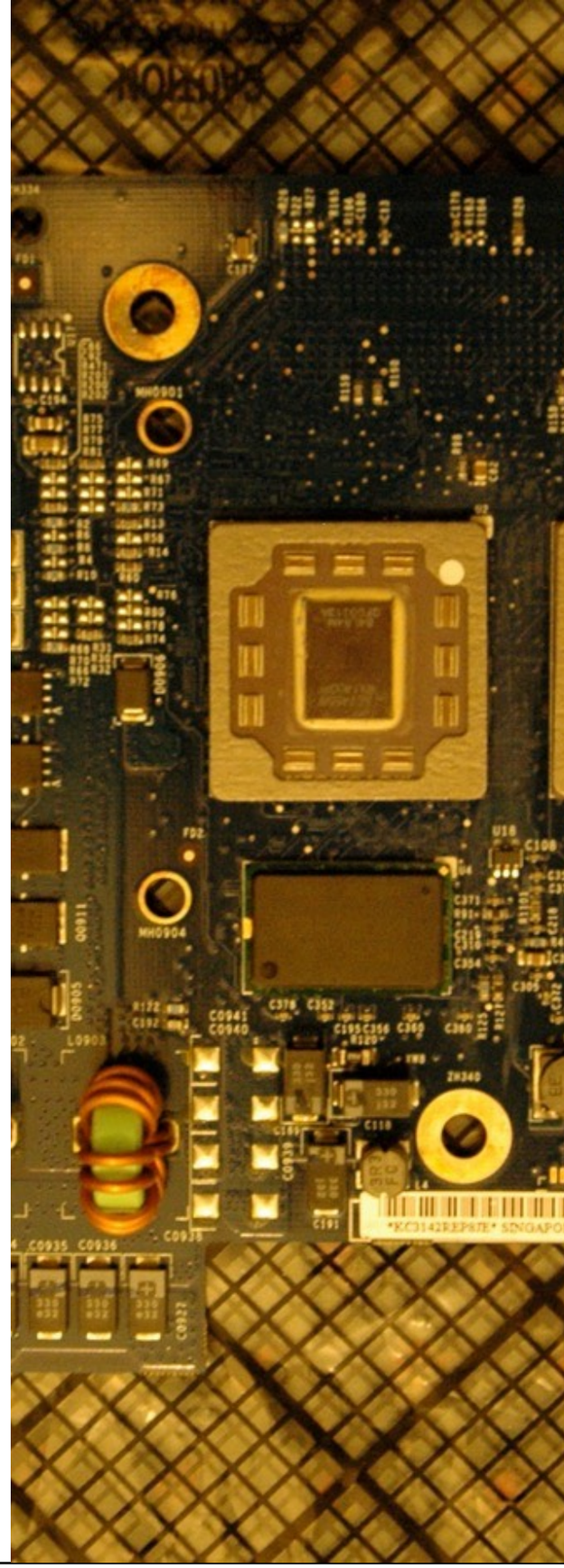
new stack frame



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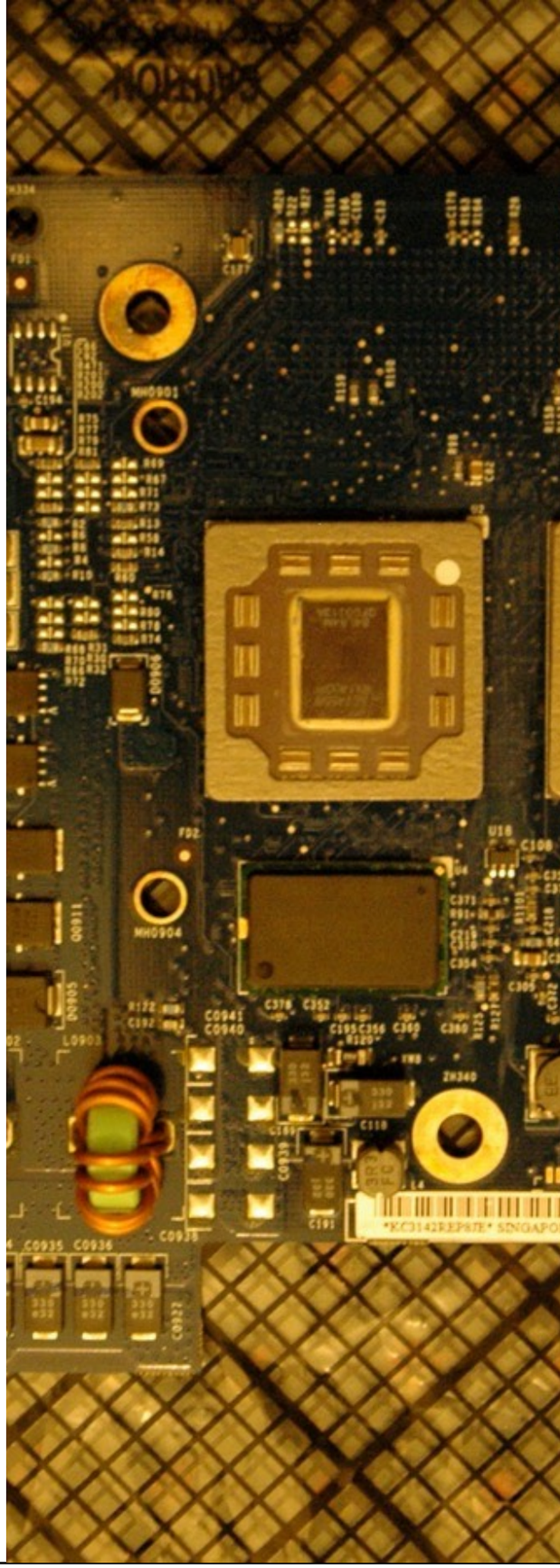
new stack frame

access parameter



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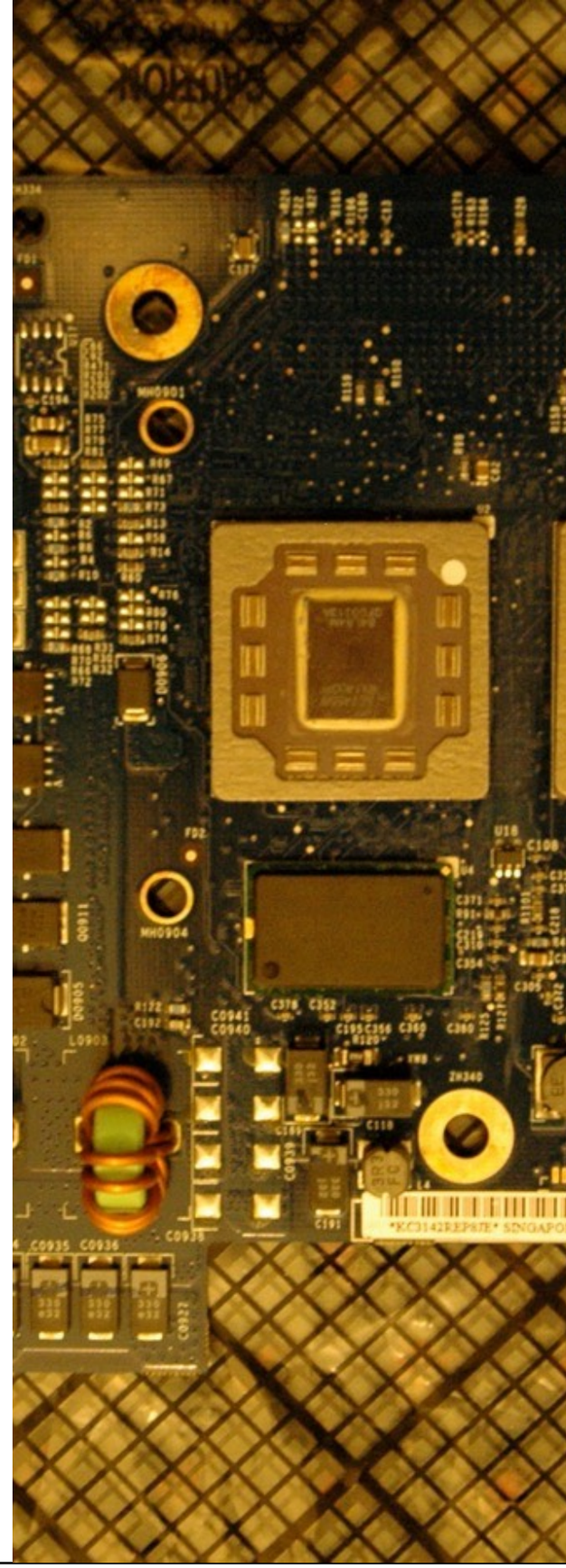
access parameter

old stack frame



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pass parameter

free parameters

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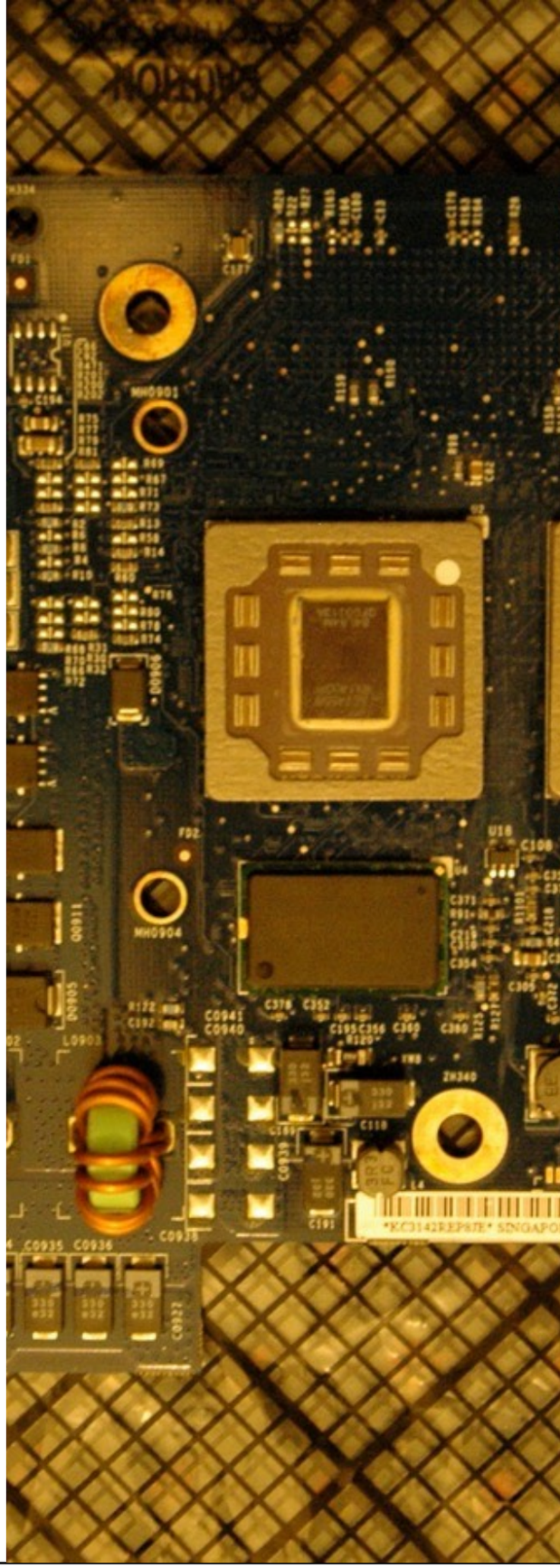
new stack frame

access parameter

old stack frame



Example: C
procedures

```c
#include <stio.h>

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

int main() {
    int x = 10 ;

    int f = fac( x ) ;
    int x printf("%d! = %d\n", x, f);
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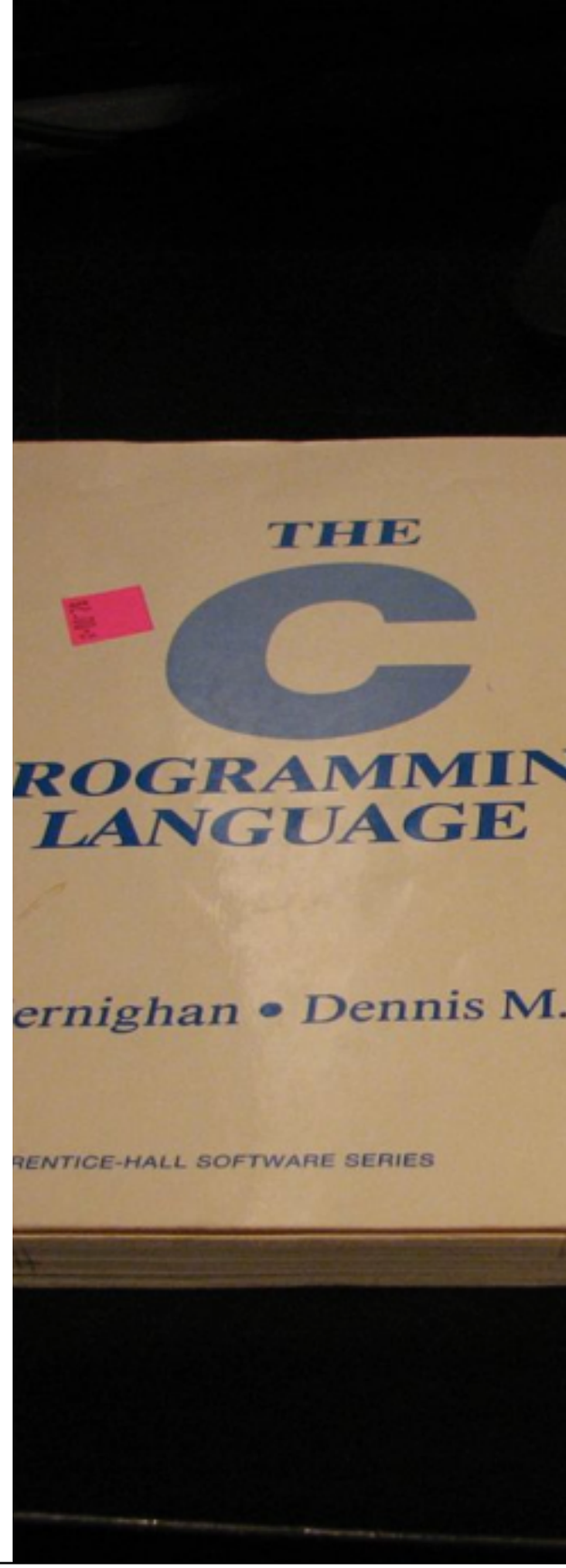

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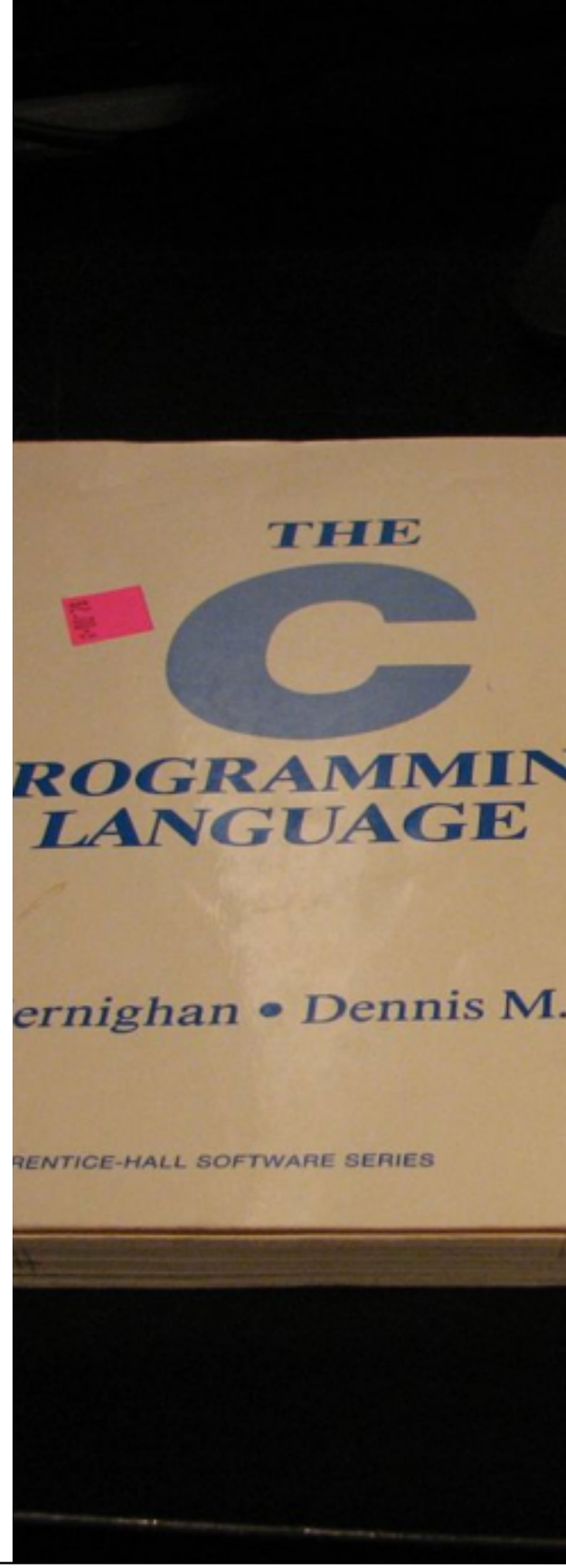
formal parameter



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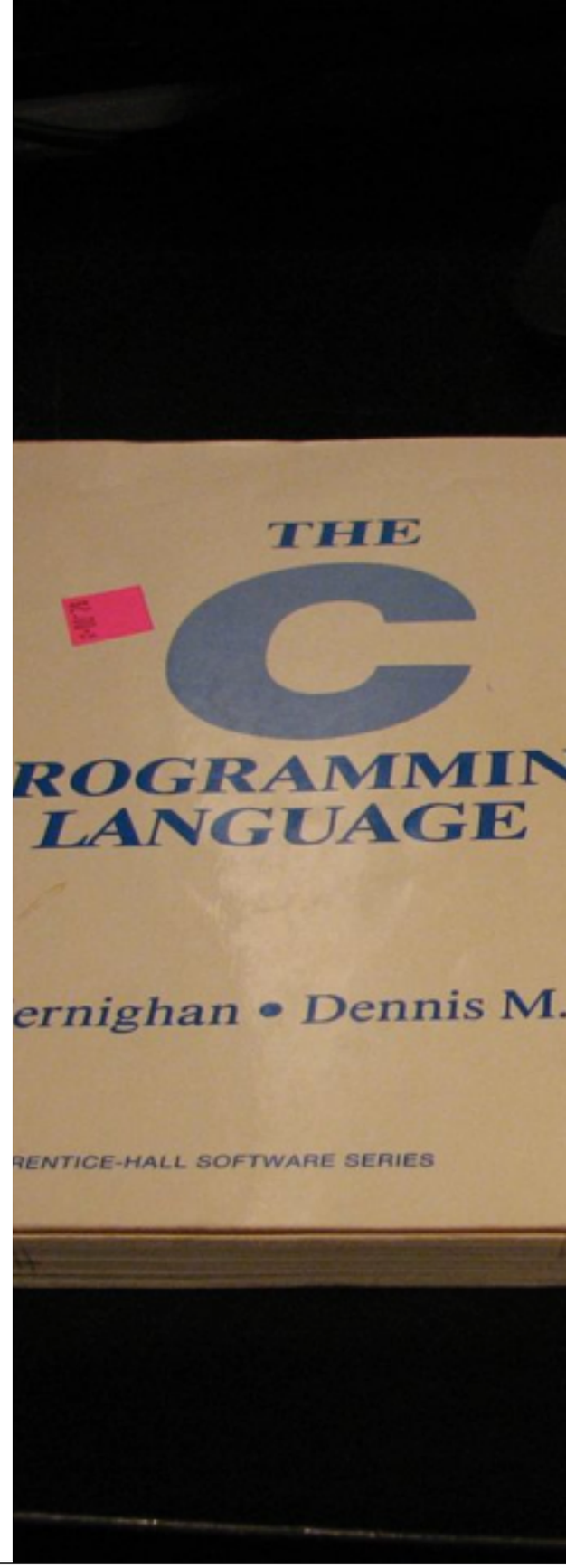
formal parameter

actual parameter



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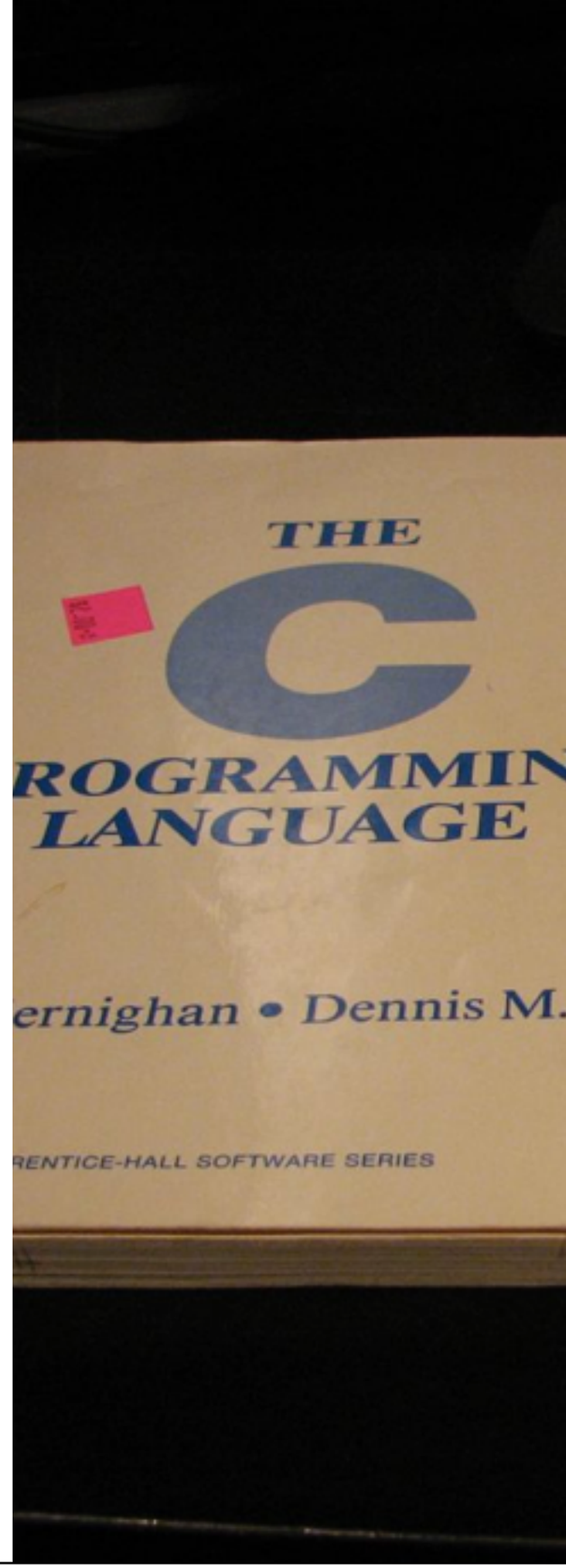
formal parameter

local variable

actual parameter



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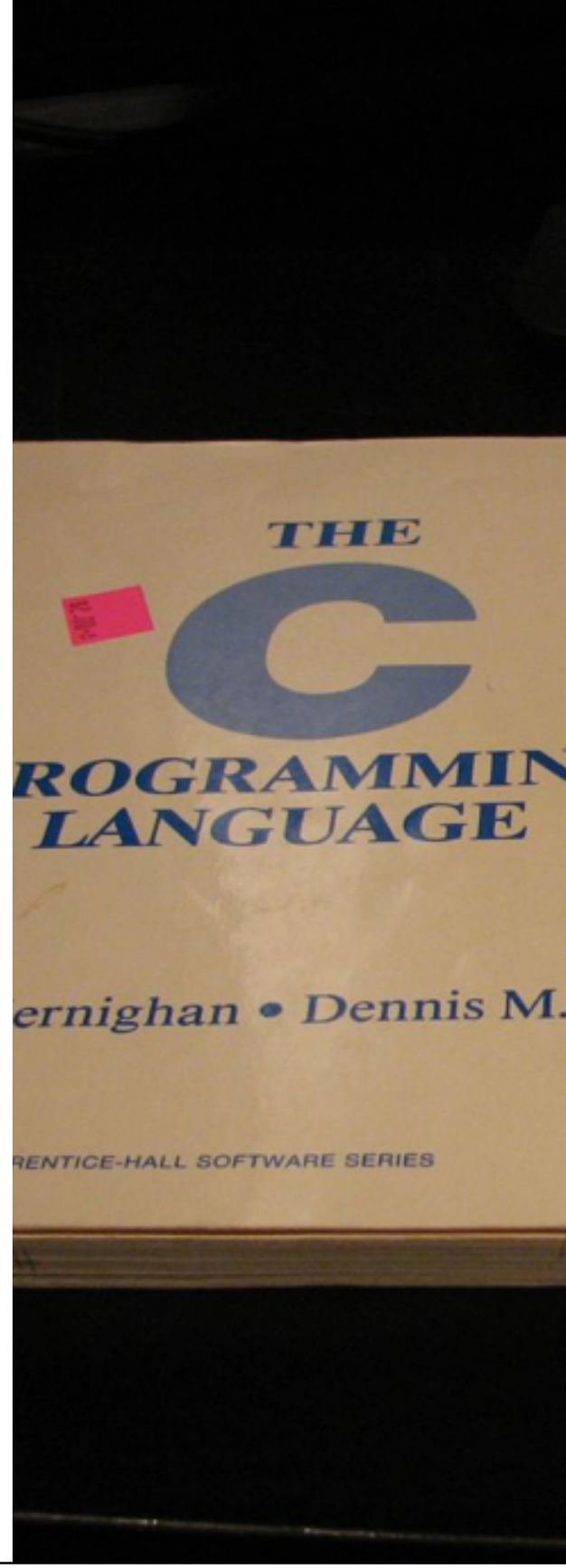
formal parameter

recursive call

local variable

actual parameter



Example: Tiger
procedures

```
/* 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
```

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formal parameter

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    var x := 5
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    f := fac( x )
end
```

formal parameter

local variable

recursive call

actual parameter

Example: Tiger

call by value vs. call by reference

```
let
    type vector = array of int

    function init(v: vector) =
        v := vector[5] of 0

    function upto(v: vector, l: int) =
        for i := 0 to l do
            v[i] := i

    var v : vector := vector[5] of 1
in
    init(v) ;
    upto(v, 5)
end
```

Imperative Languages

types

Types & Type Checking

Subtitle Text

Type

- type is category of values
- operation can be applied to all values in some category

Type checking

- safety: ensure that operation is applied to right input values
- static: check during compile time
- dynamic: check during execution

Type Systems
dynamic & static typing

Machine code

- memory: no type information
- instructions: assume values of certain types

Type Systems
dynamic & static typing

Machine code

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Dynamically typed languages

- typed values
- run-time checking & run-time errors

Type Systems

dynamic & static typing

Machine code

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Dynamically typed languages

- typed values
- run-time checking & run-time errors

Statically typed languages

- typed expressions
- compile-time checking & compile-time errors

Type Systems
compatibility

Type compatibility

- value/expression: actual type
- context: expected type

Type Systems
compatibility

Type compatibility

- value/expression: actual type
- context: expected type

Type equivalence

- structural type systems
- nominal type systems

Type Systems
compatibility

Type compatibility

- value/expression: actual type
- context: expected type

Type equivalence

- structural type systems
- nominal type systems

Subtyping

- relation between types
- value/expression: multiple types

Example: Tiger

type compatibility

```
let
    type A = int
    type B = int
    type V = array of A
    type W = V
    type X = array of A
    type Y = array of B

    var a: A := 42
    var b: B := a
    var v: V := V[42] of b
    var w: W := v
    var x: X := w
    var y: Y := x
in
    y
end
```

Type Systems
record types

Record

- consecutively stored values
- fields accessible via different offsets

Record type

- fields by name, type, position in record
- structural subtyping

```
type R1 = {f1 : int, f2 : int}
type R2 = {f1 : int, f2 : int, f3 : int}
type R3 = {f1 : byte, f2 : byte}
```

Polymorphism

biology

Polymorphism

biology

Polymorphism

biology

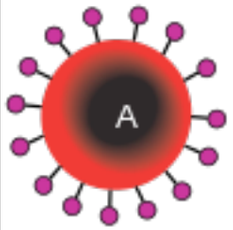
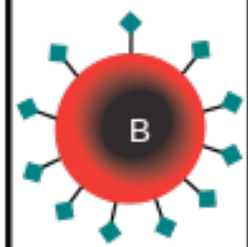
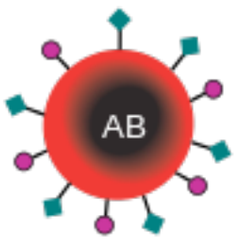
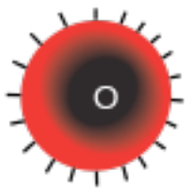
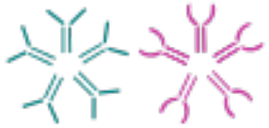
Polymorphism

biology

the occurrence of more than one form

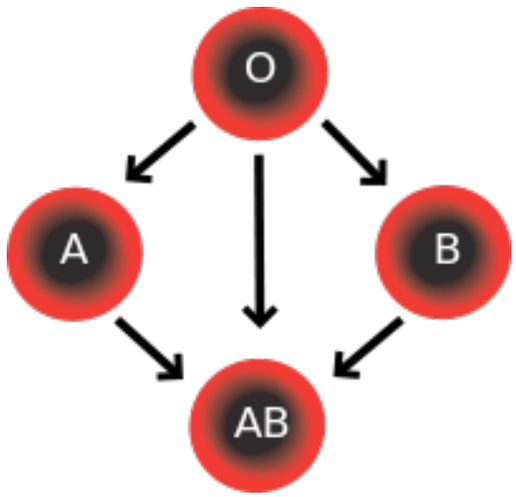
Polymorphism

biology

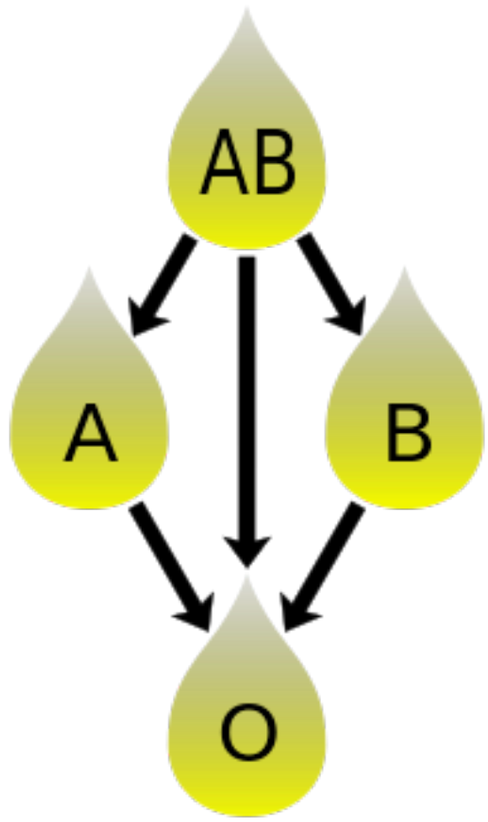
	Group A	Group B	Group AB	Group O
Red blood cell type				
Antibodies in Plasma	 Anti-B	 Anti-A	None	 Anti-A and Anti-B
Antigens in Red Blood Cell	A antigen	B antigen	 A and B antigens	None

Polymorphism

biology



can give blood to



can give plasma to

Polymorphism

programming languages

Polymorphism

programming languages

21 + 21

Polymorphism

programming languages

```
21 + 21
```

```
21.0 + 21.0
```

Polymorphism

programming languages

```
21 + 21
```

```
21.0 + 21.0
```

```
"foo" + "bar"
```

Polymorphism

programming languages

```
print(42)
```

```
print(42.0)
```

```
print("foo")
```

Polymorphism

programming languages

```
21 + 21
```

```
21.0 + 21.0
```

```
21 + 21.0
```

```
21 + "bar"
```

Type Systems
polymorphism

Ad-hoc polymorphism

overloading

- same name, different types, same operation
- same name, different types, different operations

type coercion

- implicit conversion

Universal polymorphism

subtype polymorphism

- substitution principle

parametric polymorphism

```
21 + 21
21.0 + 21.0

print(42)
print(42.0)

"foo" + "bar"

21 + "bar"
```

Object-Oriented Languages

objects & messages

Modularity

objects & messages

Objects

- generalization of records
- identity
- state
- behavior

Modularity

objects & messages

Objects

- generalization of records
- identity
- state
- behavior

Messages

- objects send and receive messages
- trigger behavior
- imperative realization: method calls

Object-Oriented Languages types

Modularity
classes

Classes

- generalization of record types
- characteristics of objects: attributes, fields, properties
- behavior of objects: methods, operations, features

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

Modularity
classes

Classes

- generalization of record types
- characteristics of objects: attributes, fields, properties
- behavior 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; }
}
```

Modularity

inheritance vs. interfaces

Inheritance

- inherit attributes & methods
- additional attributes & methods
- override behavior
- nominal 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'() {…}
}
```

Modularity

inheritance vs. interfaces

Inheritance

- inherit attributes & methods
- additional attributes & methods
- override behavior
- nominal subtyping

Interfaces

- avoid multiple inheritance
- interface: contract for attributes & methods
- class: provides attributes & methods
- nominal 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'() {…}
}
```

Type Systems
polymorphism

Type Systems
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

Type Systems
polymorphism

Ad-hoc polymorphism

overloading

- same method name, independent classes
- same method name, same class, different parameter types

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- same method name, subclass, compatible types

Universal polymorphism

subtype polymorphism

- inheritance, interfaces

parametric polymorphism

Type Systems
static vs. dynamic dispatch

Dispatch

- link method call to method

Type Systems

static vs. dynamic dispatch

Dispatch

- link method call to method

Static dispatch

- type information at compile-time

Type Systems

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: Java

single dispatch

```
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);
```

Example: Java

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 G {
   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);
```

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