Laboratorio di Programmazione 3

Lezioni 18, 19 e 20: Portabilità e Sicurezza, Java (cap. 13)

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Versione modificata delle slides di J. C. Mitchell fornite con il libro "Concepts in Programming Languages" come materiale di supporto alla didattica

Origins of the language

- James Gosling and others at Sun, 1990 - 95
- Oak language for “set-top box”
  - small networked device with television display
    - graphics
    - execution of simple programs
    - communication between local program and remote site
    - no “expert programmer” to deal with crash, etc.
- Internet application
  - simple language for writing programs that can be transmitted over network

Design Goals

- Portability
  - Internet-wide distribution: PC, Unix, Mac
- Reliability
  - Avoid program crashes and error messages
- Safety
  - Programmer may be malicious
- Simplicity and familiarity
  - Appeal to average programmer; less complex than C++
- Efficiency
  - Important but secondary

General design decisions

- Simplicity
  - *Almost* everything is an object
  - All objects accessed through pointers (they are all on the heap) and pointer assignment is the only form of object assignment
  - No functions, no multiple inheritance, no *operator overloading*, few automatic coercions (*much simpler than C++*)
  - Always pass parameters to Java methods by value (*pass-by-value*)
- Portability and network transfer
  - Bytecode interpreter on many platforms (*the JVM*)
  - Dynamic linking
- Reliability and Safety
  - Typed source and typed bytecode language (compile-time type checks by the compiler)
  - Run-time type and bounds checks (by the JVM)
  - Garbage collection

You can see that many of the above decisions decrease efficiency.

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Java System

- The Java programming language
- Compiler and run-time system
  - Programmer compiles code
  - Compiled code transmitted on network
  - Receiver executes on interpreter (JVM)
  - Safety checks made before/during execution
- Library, including graphics, security, etc.
  - Large library made it easier for projects to adopt Java
  - Language interoperability
    - Provision for “native” methods (efficiency and access to legacy utilities)

Outline

- Objects in Java
  - Classes, encapsulation, inheritance
- Type system
  - Primitive types, interfaces, arrays, exceptions
- Generics (added in Java 1.5)
  - Basics, wildcards, …
- Virtual machine
  - Loader, verifier, linker, interpreter
  - Bytecodes for method lookup
- Security issues

Language Terminology

- Class, object - as in other languages
- Field – data member
- Method - member function
- Static members - class fields and methods
- this - self
- Package - set of classes in shared namespace
- Native method - method written in another language, often C

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Java Classes and Objects

- Syntax similar to C++
- Object
  - has fields and methods
  - is allocated on heap, not run-time stack
  - accessible through reference (only ptr assignment)
  - garbage collected
- Dynamic lookup
  - Similar in behavior to other languages

Point Class

```
class Point {
    private int x;
    protected void setX (int y)  {x = y;}
    public int  getX()     {return x;}
    Point(int xval) {x = xval;}       // constructor
};
```

– Visibility similar to C++, but not exactly (later slide)

Object initialization

- Java guarantees constructor call for each object
  - Memory allocated
  - Constructor called to initialize memory
  - Some interesting issues related to inheritance

    We'll discuss later …
- Cannot do this (would be bad C++ style anyway):
  - Obj* obj = (Obj*)malloc(sizeof(Obj));
- Static fields of class initialized at class load time
  - Talk about class loading later

Static fields and methods

```
class Pippo {
  static int x;
  static { /* code to be executed once, when class is loaded */}
}
```

- They can access only static fields and other static methods.
- Some other restrictions, e.g., a static block cannot raise an exception

An example:

```
public class MyProgramMainClass {
  …
  public static void main(String[] args) {…} …}
```

As an excerpt from “Concepts in Programming Languages” – Chapter 13

Garbage Collection and Finalize

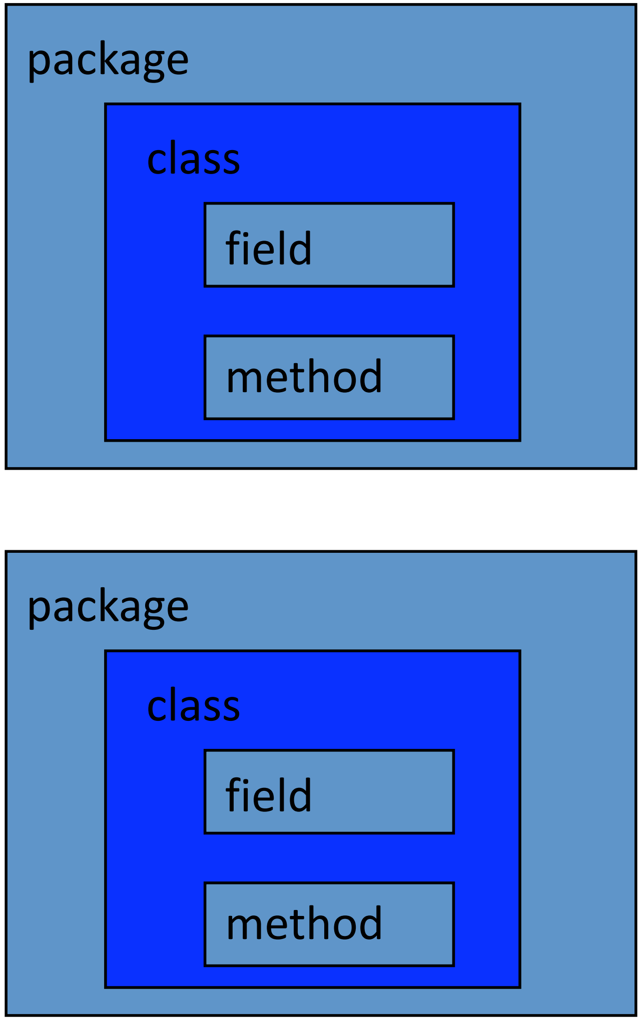
- Objects are garbage collected
  - No explicit *free*
  - Avoids dangling pointers and resulting type errors
- Problem
  - What if object has opened file or holds lock?
- Solution
  - *finalize* method, called by the garbage collector
    - Before space is reclaimed, or when virtual machine exits
    - portant convention: call super.finalize

```
class … {…
  protected void finalize () { super.finalize(); close(file);}};
```

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Encapsulation and packages

- Every field, method belongs to a class
- Every class is part of some package
  - Can be unnamed default package
  - File declares which package code belongs to



As an excerpt from "Concepts in Programming Languages" – Chapter 13

Visibility and access

- Four visibility distinctions
  - public: accessible anywhere the class is visible
  - protected: accessible to methods of the class and any subclasses, as well as to other classes in the same package,
  - private: accessible only in the class itself,
  - package (default visibility): accessible only to code in the same package (not visible to subclasses in other packages)
- In other words, method can refer to
  - private members of class it belongs to
  - non-private members of all classes in same package
  - protected members of superclasses (in diff package)
  - public members of classes in visible packages

    Visibility determined by files system, etc. (outside language)
- Qualified names (or use import)
  - $\underbrace{\text{java.lang}}_{\text{package}}.\underbrace{\text{String}}_{\text{class}}.\underbrace{\text{substring()}}_{\text{method}}$

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Inheritance

- Similar to Smalltalk, C++
  - method overriding (keyword *super*) and field hiding
  - constructors (keyword *super,* implicitly by the programmer or explicitly by the compiler… different from the *finalize* case)
- *Subclass* inherits from *superclass*
  - Single inheritance only (but Java has interfaces… see later)
  - *Interface* different from *abstract class*, no names clash… a more clean feature
- Some additional features
  - Conventions regarding *super* in constructor and *finalize* methods
  - Final classes and methods
    - Singleton pattern, java.lang.System class, …

Example subclass

```
class ColorPoint extends Point {
  // Additional fields and methods
   private Color c;
   protected void setC (Color d)  {c = d;}
   public Color  getC()     {return c;}
  // Define constructor
   ColorPoint(int xval, Color cval) {
        super(xval);    // call Point constructor
        c = cval;  }     // initialize ColorPoint field
 };
```

As an excerpt from “Concepts in Programming Languages” – Chapter 13

Class *Object*

- Every class extends another class
  - Superclass is *Object* if no other class named
- Methods of class *Object* (is the one class that has no superclasses)
  - GetClass – return the Class object representing class of the object, used for reflection purposes
  - ToString – returns string representation of object
  - equals – default object equality (not ptr equality)
  - hashCode – returns an integer that can be used to store the object in a has table
  - clone – makes a duplicate of an object
  - wait, notify, notifyAll – used with concurrency
  - finalize – which is run just before an object is destroyed
- Every object that we create has at least the above methods

Constructors and Super

- Java guarantees constructor call for each object
- This must be preserved by inheritance
  – Subclass constructor must call super constructor
    - If first statement is not call to super, then call super() inserted automatically by compiler
    - If superclass does not have a constructor with no args, then this causes compiler error (yuck)
    - Exception to rule: if one constructor invokes another, then it is responsibility of second constructor to call super, e.g.,

      ```
      ColorPoint() { ColorPoint(0,blue);}
      ```

      is compiled without inserting call to super
- Different conventions for finalize and super
    - Compiler does not force call to super finalize

Final classes and methods

- Restrict inheritance
  - Final classes and methods cannot be redefined
- Example

  java.lang.String
- Reasons for this feature
  - Important for security
    - Programmer controls behavior of all subclasses
    - Critical because subclasses produce subtypes
  - Compare to C++ virtual/non-virtual
    - Method is "virtual" until it becomes final

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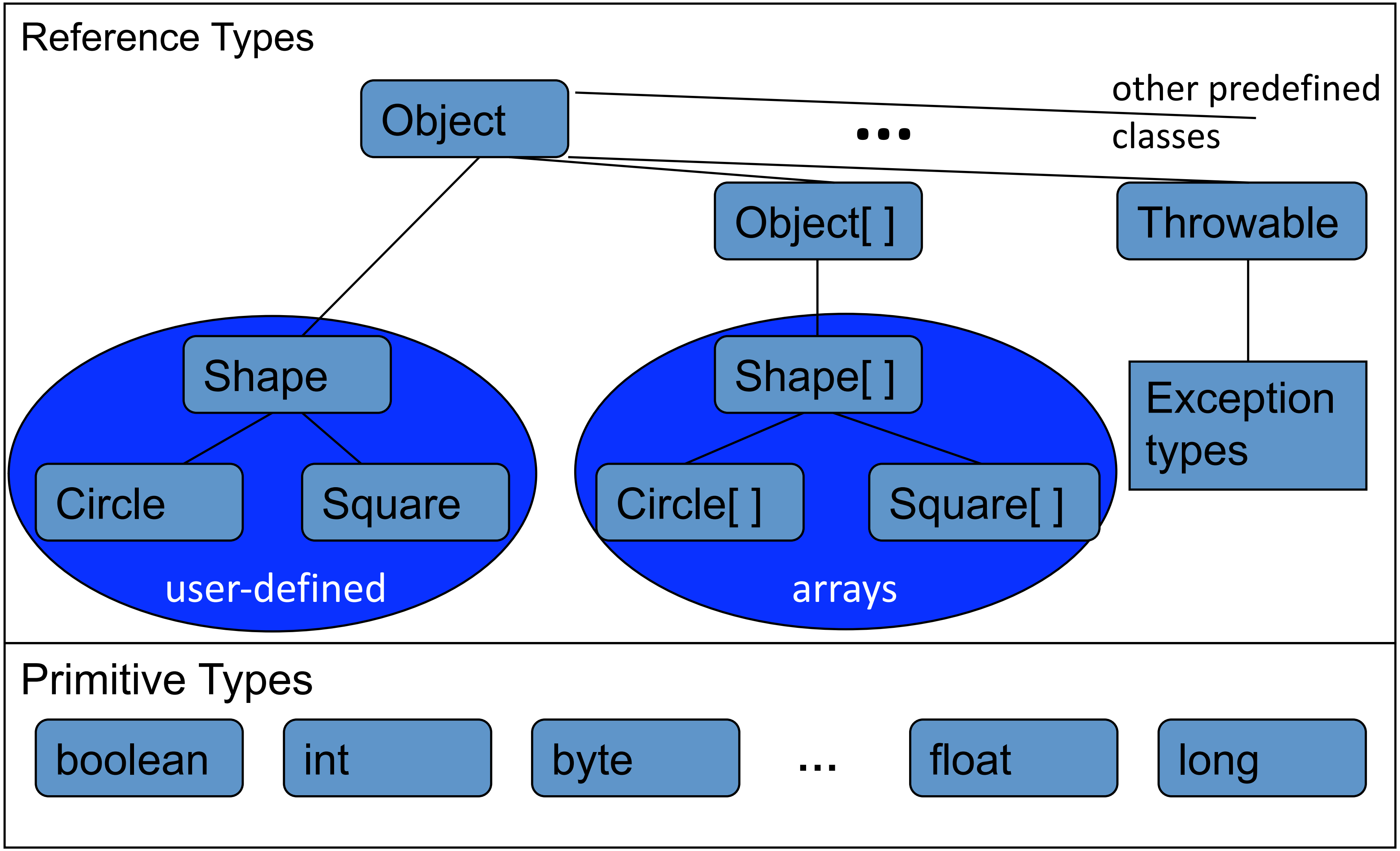
Java Types

- Two general kinds of types
  - Primitive types – *not* objects
    - Integers, Booleans, etc
  - Reference types
    - Classes, interfaces, arrays
    - No syntax distinguishing Object * from Object
- Static type checking
  - Every expression has type, determined from its parts
  - Some auto conversions, many casts are checked at run time
  - Example, assuming A <: B
    - If A x, then can use x as argument to method that requires B
    - If B x, then can try to cast x to A
    - Downcast checked at run-time, may raise exception

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Classification of Java types



As an excerpt from "Concepts in Programming Languages" – Chapter 13

Subtyping

(unique form of sub-classing in Java, no inheritance without subtyping as in C++ through private base classes)

- Primitive types
  - Conversions: int -> long, double -> long, …
  - e.g., *Object* objects in a *LinkedList* – type cast checked at run-time, it raises an exception if the referenced object does not have the designated type
- Class subtyping similar to C++
  - Subclass produces subtype
  - Single inheritance => subclasses form tree
- Interfaces
  - Completely abstract classes
    - no implementation
  - Multiple subtyping
    - Interface can have multiple subtypes (implements, extends)
    - It allows objects to support (multiple) common behaviors without sharing any common implementation
- Arrays
  - Covariant subtyping – not consistent with semantic principles… see later

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Java class subtyping

- Signature Conformance
  - Subclass method signatures must conform to those of superclass
- Three ways signature could vary
  - Argument types
  - Return type
  - Exceptions

Interface subtyping: example

```
interface Shape {
   public float center();
  public void rotate(float degrees);
}
interface Drawable {
   public void setColor(Color c);
  public void draw();
}
class Circle implements Shape, Drawable {
   // does not inherit any implementation
  // but must define Shape, Drawable methods
}
```

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Properties of interfaces

- Flexibility
  - Allows subtype graph instead of tree
  - Avoids problems with multiple inheritance of implementations (remember C++ “diamond”)
- Cost
  - Offset in method lookup table not known at compile
  - Different bytecodes for method lookup
    - one when class is known
    - one when only interface is known
      - search for location of method
      - cache for use next time this call is made (from this line)

    More about this later …

Array types

- Automatically defined
  - Array type T[ ] exists for each class, interface type T
  - Cannot extended array types (array types are final)
  - Multi-dimensional arrays are arrays of arrays: T[ ] [ ]
- Treated as reference type
  - An array variable is a pointer to an array, can be null
  - Example: `Circle[] x = new Circle[array_size]`
  - Anonymous array expression: `new int[] {1,2,3, ... 10}`
- Every array type is a subtype of Object[ ], Object
  - Length of array is not part of its static type (e.g., Circle[])

Array subtyping

- Covariance
  - if S <: T then S[ ] <: T[ ] (this is just a design choice)
- Standard type error (*array covariance problem*)

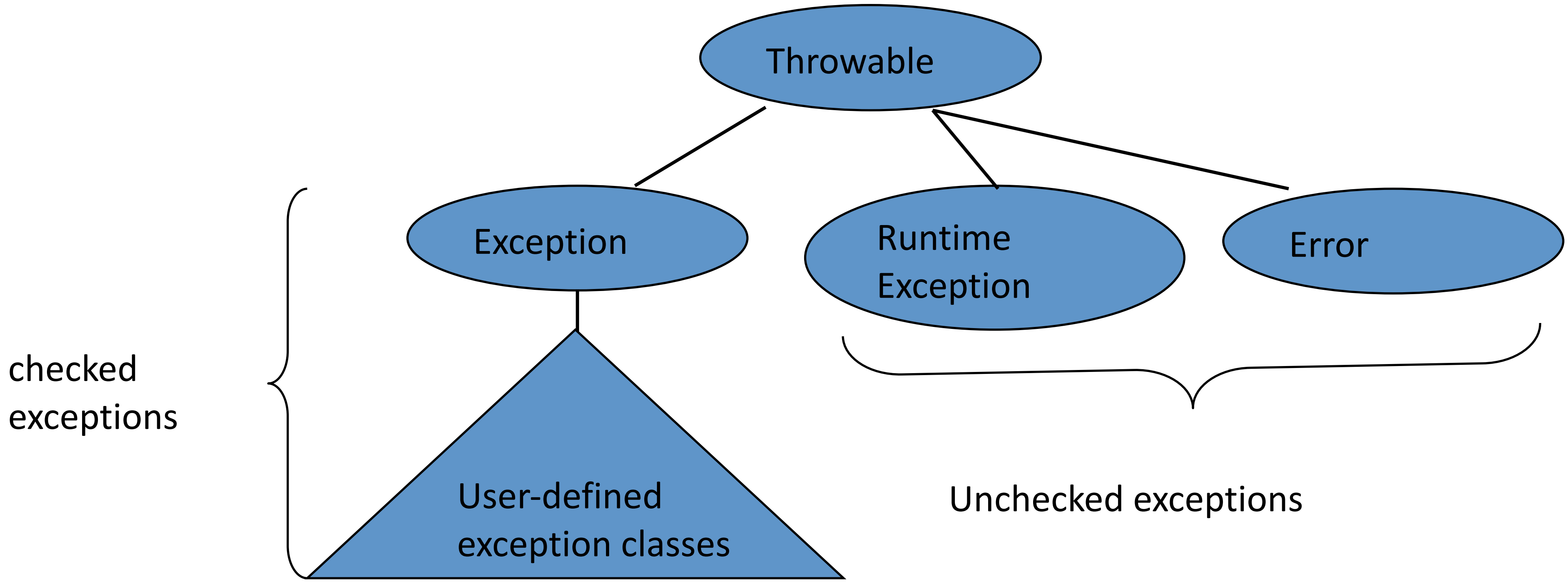
```
class A {…}
class B extends A {…}
B[ ] bArray = new B[10]
A[ ] aArray = bArray      // considered OK since B[] <: A[]
aArray[0] = new A()       // compiles, but run-time error
                          // raises ArrayStoreException
```

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Java Exceptions

- Similar basic functionality to ML, C++
  - Constructs to *throw* and *catch* exceptions
  - Dynamic scoping of handler
- Some differences
  - An exception is an object from an exception class (all subtypes of *Throwable*)
    - <u>advantage</u>: useful info is stored in the exception object hence allowing one to carry information from the point in which the exception has been thrown to the handler that catches it
  - Subtyping between exception classes
    - Use subtyping to match type of exception or pass it on …
    - Similar functionality to ML pattern matching in handler
    - <u>A handler matches the class of an exception if it names either the same class or a superclass</u>
  - Type of method includes exceptions it can throw
    - Actually, only subclasses of Exception (see next slide)

Exception Classes



- If a method may throw a checked exception, then this must be in the type of the method

As an excerpt from "Concepts in Programming Languages" – Chapter 13

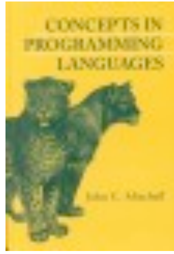
Try/finally blocks

- Exceptions are caught in try blocks

```
try {
        statements
}    catch (ex-type1 identifier1) {
          statements
} catch (ex-type2 identifier2) {
          statements
}  finally {
          statements
}
```

Lesson learned ☺ :

read carefully



try through the Java compiler

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Why define new exception types?

- Exception may contain data
  - Class Throwable includes a string field so that cause of exception can be described
  - Pass other data by declaring additional fields or methods
- Subtype hierarchy used to catch exceptions

  catch <exception-type> <identifier> { … }

  will catch any exception from any subtype of exception-type and bind object to identifier

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Java Generic Programming

- Java has class Object
  - Supertype of all object types
  - This allows “subtype polymorphism”
    - Can apply operation on class T to any subclass S <: T
- Java 1.0 – 1.4 did not have templates
  - No parametric polymorphism
  - Many considered this the biggest deficiency of Java
- Java type system does not let you “cheat”
  - Can cast from supertype to subtype
  - Cast is checked at run time

Example generic construct: Stack

- Stacks possible for any type of object
  - For any type t, can have type stack_of_t
  - Operations push, pop work for any type
- In C++, would write generic stack class

```
template <type t> class Stack {
 private: t data;  Stack<t> * next;
 public: void    push (t* x) { … }
                t*  pop   (     ) { … }
};
```

- What can we do in Java 1.0?

Java 1.0 vs Generics

```
class Stack {
  void push(Object o)  { ... }
  Object pop() { ... }
  ...}

String s = "Hello";
Stack st = new Stack();
...
st.push(s);
...
s = (String) st.pop();
```

a run-time check is needed

```
class Stack<A> {
  void push(A a) { ... }
  A pop() { ... }
  ...}

String s = "Hello";
Stack<String> st =
        new  Stack<String>();
st.push(s);
...
s = st.pop();
```

no run-time check

clarity

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Why no generics in early Java ?

- Many proposals
- Basic language goals seem clear
- Details take some effort to work out
  – easy implementation (homogeneous implementation)
    - from Java with templates to Java without templates
    - efficiency decreases, many run-time-checked type conversions
  – alternative implementation
    - compile generic class in a form of class file that has type parameters and load the instantiation of the generic class by instantiating this class file at class-load time
    - more efficient code, but more classes to be loaded (class loading is slow)

Java Community proposal (JSR 14) incorporated into Java 1.5

Java 1.5 Implementation

- Homogeneous implementation

```
class Stack<A> {
  void push(A a) { ... }
  A pop() { ... }
  ...}
```

```
class Stack {
  void push(Object o)  { ... }
  Object pop() { ... }
  ...}
```

- Algorithm
  - replace class parameter <A> by Object, insert casts
  - if <A extends B>, replace A by B
- Why choose this implementation?
  - Backward compatibility of distributed bytecode
  - Surprise: sometimes faster because class loading slow

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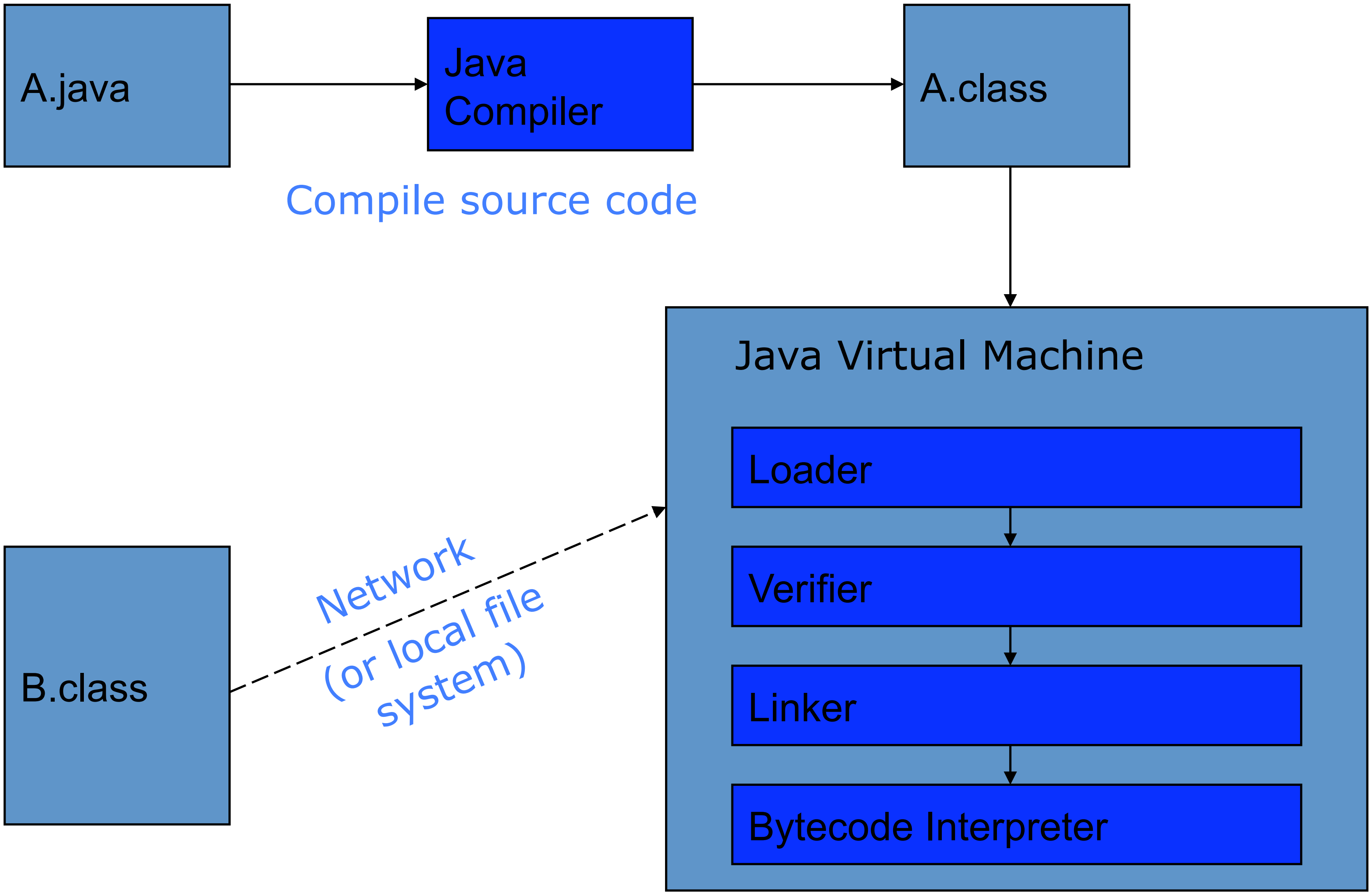
  - Bytecode verifier (example: initialize before use)
  - Implementation of generics
- Security issues

Java Implementation

- Compiler and Virtual Machine
  - Compiler produces bytecode
  - Virtual machine loads classes on demand, verifies bytecode properties, interprets bytecode
- Why this design?
  - Bytecode interpreter/compilers used before
    - Pascal “pcode”; Smalltalk compilers use bytecode
  - Minimize machine-dependent part of implementation
    - Do optimization on bytecode when possible
    - Keep bytecode interpreter simple
  - For Java, this gives portability
    - Transmit bytecode across network

Java Virtual Machine Architecture



As an excerpt from "Concepts in Programming Languages" – Chapter 13

Class loader

- Runtime system loads classes as needed
  - When class is referenced, loader searches for file of compiled bytecode instructions
- Default loading mechanism can be replaced
  - Define alternate ClassLoader object
    - Extend the abstract ClassLoader class and implementation
    - ClassLoader does not implement abstract method loadClass, but has methods that can be used to implement loadClass
  - Can obtain bytecodes from alternate/remote source

JVM Linker and Verifier

- Linker
  - Adds compiled class or interface to runtime system
  - Creates static fields and initializes them
  - Resolves names
    - Checks symbolic names and replaces with direct references
- Verifier
  - Check bytecode of a class or interface before loaded
  - Throw VerifyError exception if error occurs

Verifier

- Verifier checks correctness of bytecode
  - Every instruction must have a valid operation code
  - Every branch instruction must branch to the start of some other instruction, not middle of instruction
  - Every method must have a structurally correct signature
  - Every instruction obeys the Java type discipline

Last condition is fairly complicated

Bytecode interpreter

- Standard virtual machine interprets instructions
  - Perform run-time checks such as array bounds
  - Possible to compile bytecode class file to native code
- Java programs can call native methods
  - Typically functions written in C
- Multiple bytecodes for method lookup
  - invokevirtual - when a superclass of the object is known at compile-time
  - invokeinterface - when only an interface of the object is known at compile-time
  - invokestatic - static methods
  - invokespecial - some special case (not discussed)

Type Safety of JVM

- Run-time type checking
  - All casts are checked to make sure type safe
  - All array references are checked to make sure the array index is within the array bounds
  - References are tested to make sure they are not null before they are dereferenced.
- Additional features
  - Automatic garbage collection
  - No pointer arithmetic

  If program accesses memory, that memory is allocated to the program and declared with correct type

As an excerpt from "Concepts in Programming Languages" – Chapter 13

JVM uses stack machine

- Java

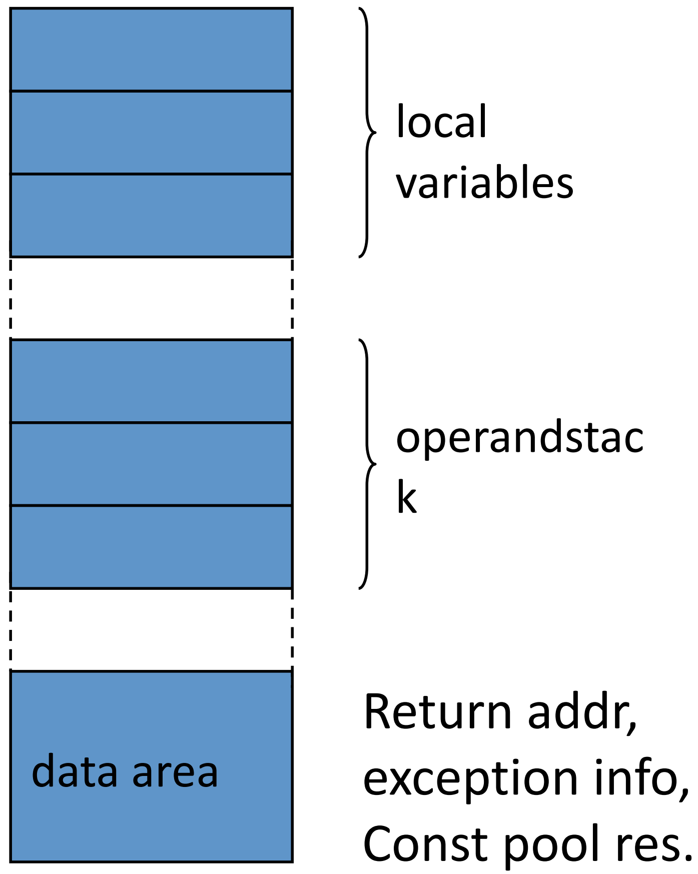
```
Class A extends Object {
    int i
    void f(int val) { i = val + 1;}
}
```

- Bytecode

```
Method void f(int)
    aload 0    ; object ref this
    iload 1    ; int val
    iconst 1
    iadd       ; add val +1
    putfield #4 <Field int i>
    return
```

refers to const pool

JVM Activation Record



Field and method access

- Instruction includes index into constant pool
  - Constant pool stores symbolic names
  - Store once, instead of each instruction, to save space
- First execution
  - Use symbolic name to find field or method
  - E.g., getfield #18 <Field Obj var>
- Second execution
  - Use modified "quick" instruction to simplify search
  - getfield_quick 6 (*the field has been found and it was located 6 bytes below the first location of the object*)

As an excerpt from "Concepts in Programming Languages" – Chapter 13

invokeinterface <method-spec>

- Sample code

  ```
  void add2(Incrementable x) { x.inc(); x.inc(); }
  ```

- Search for method
  - find class of the object operand (operand on stack)
    - must implement the interface named in <method-spec>
  - search the method table for this class
  - find method with the given name and signature
- Call the method
  - Usual function call with new activation record, etc.

Why is search necessary?

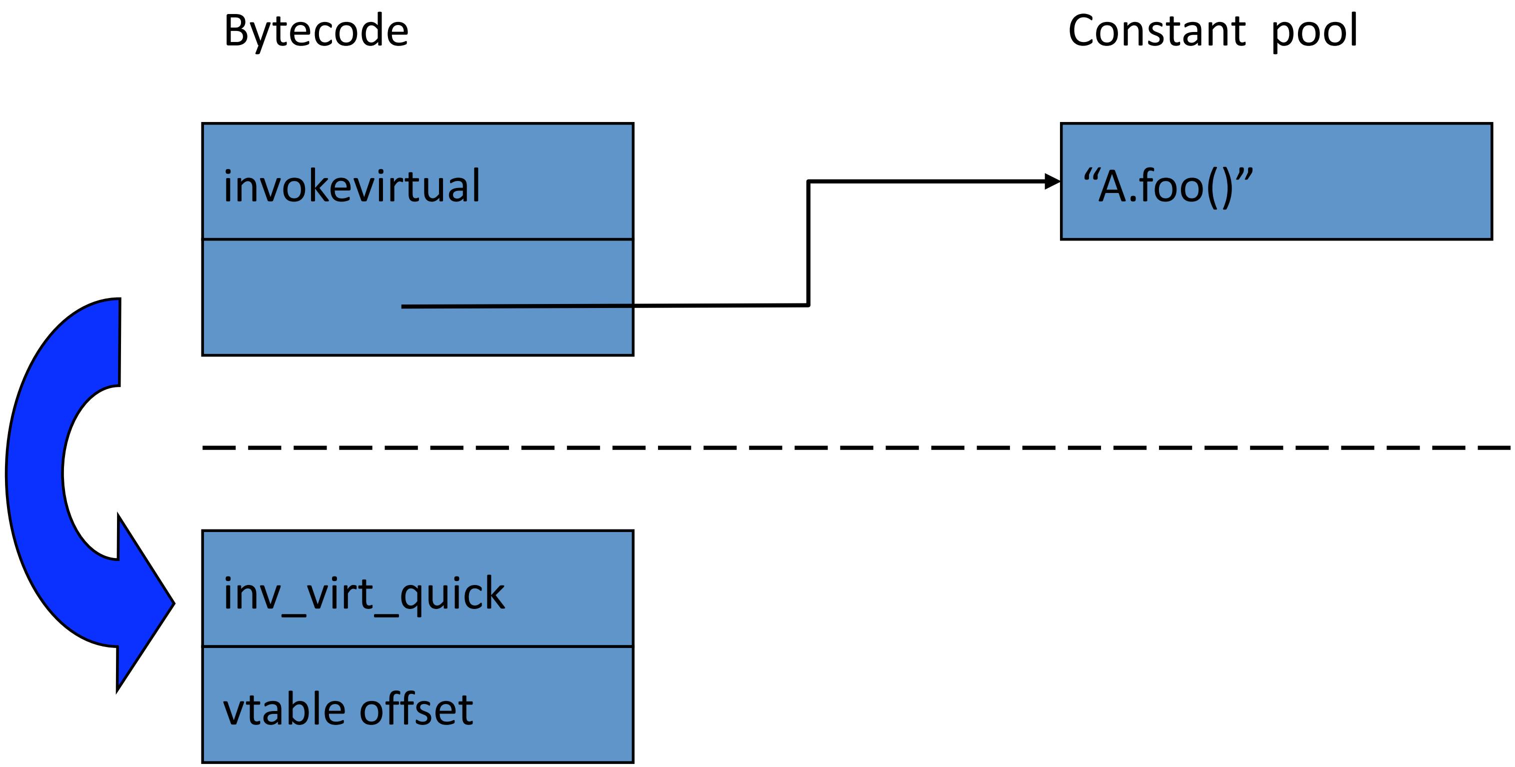
```
interface Incrementable {
    public void inc();
}
class IntCounter implements Incrementable {
    public void add(int);
    public void inc();
   public int value();
}
class FloatCounter implements Incrementable {
    public void inc();
    public void add(float);
    public float value();
}
```

As an excerpt from "Concepts in Programming Languages" – Chapter 13

invokevirtual <method-spec>

- Similar to invokeinterface, but the superclass is known at compile-time
- Search for method
  - search the method table of this class
  - find method with the given name and signature
- Can we use static type for efficiency?
  - Each execution of an instruction will be to object from subclass of statically-known class
  - Constant offset into vtable
    - like C++, but dynamic linking makes search useful first time
  - See next slide

Bytecode rewriting: invokevirtual



- After search, rewrite bytcode to use fixed offset into the vtable. No search on second execution.

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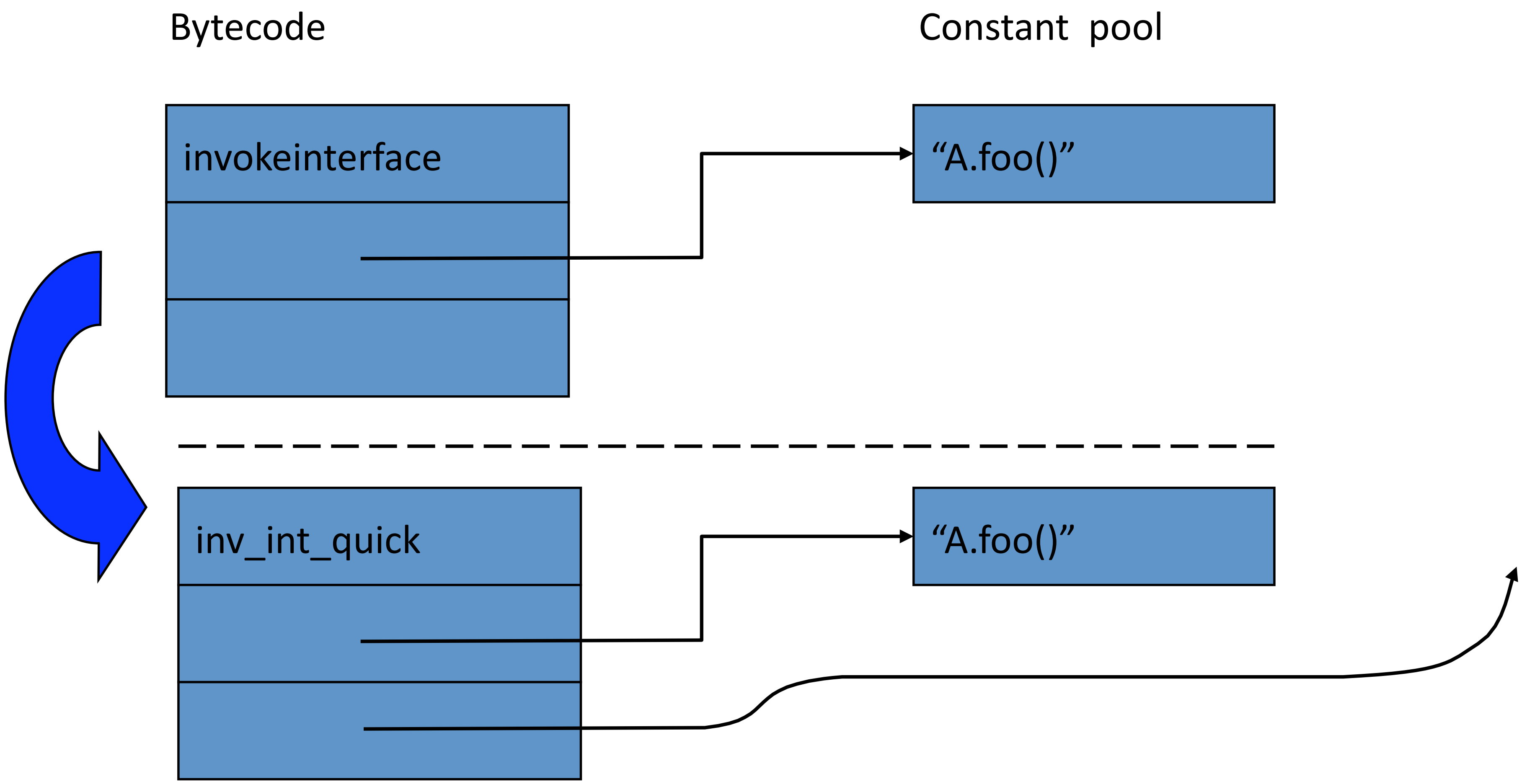
Bytecode rewriting: invokeinterface



Cache address of method; check class on second use

As an excerpt from "Concepts in Programming Languages" – Chapter 13

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  - Bytecode verifier (example: initialize before use)
  - Implementation of generics
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Java Security

- Security
  - Prevent unauthorized use of computational resources
  - E.g., Sendmail always runs as super-user process
- Java security
  - Java code can read input from careless user or malicious attacker
  - Java code can be transmitted over network – code may be *written* by careless friend or malicious attacker

Java is designed to reduce many security risks

Java Security Mechanisms

- Sandboxing
  - Run program in restricted environment
    - Analogy: child’s sandbox with only safe toys
    - when bytecode is executed, some operations that can be written in Java language might not be allowed to proceed, just the way that, when a child plays in a sandbox, an adult supervisory may give the child only those toys that the supervisor considers safe
  - This term refers to
    - Features of loader, verifier, interpreter that restrict program
    - Java Security Manager, a special object that acts as access control “gatekeeper”
- Code signing
  - Use cryptography to establish origin of class file
    - This info can be used by security manager
    - E.g., Only some code producers are allowed to execute code, different rights for different code producers

Buffer Overflow Attack

- Most prevalent security problem today
  - Approximately 80% of CERT advisories are related to buffer overflow vulnerabilities in OS, other code
- General network-based attack
  - Attacker sends carefully designed network msgs
  - Input causes privileged program (e.g., Sendmail) to do something it was not designed to do
- Does not work in Java
  - Illustrates what Java was designed to prevent

Sample C code to illustrate attack

```
void f (char *str) {
   char buffer[16];
   …
   strcpy(buffer,str);
}
void main() {
   char large_string[256];
   int i;
   for( i = 0; i < 255; i++)
       large_string[i] = 'A';
   f(large_string);
}
```

- Function
  - Copies str into buffer until null character found
  - Could write past end of buffer, *over function retun addr*
- Calling program
  - Writes 'A' over f activation record
  - Function f "returns" to location 0x4141414141
  - This causes segmentation fault
- Variations
  - Put meaningful address in string
  - Put *code* in string and jump to it !!

Not so simple in practice… it requires several attempts by the attacker

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Java Sandbox

- Four complementary mechanisms to restrict the operations of a Java bytecode
  - Class loader
    - Separation between trusted and untrusted class libraries by making it possible to load each with different class loaders
    - Separate namespaces for classes loaded by different class loaders
    - Place code into categories (associates *protection domain* with each class) that let the security manager to restrict the actions that specific code will be allowed to take
  - Verifier and JVM run-time tests
    - NO unchecked casts or other type errors, NO array overflow
      - no method will overflow the operand stack
      - no illegal data conversions (e.g., an integer to a pointer)
      - all method are called with parameter of correct type (type-confusion attacks prevention, discussed later)
    - Preserves private, protected visibility levels
  - Security Manager
    - Uses protection domain associated with code, user policy
      - code signer + class location

As an excerpt from “Concepts in Programming Languages” – Chapter 13

Security Manager

- Java library functions call security manager
- Security manager object answers at run time
  - Decide if calling code is allowed to do operation
  - Examine protection domain of calling class
    - Signer: organization that signed code before loading
    - Location: URL where the Java classes came from
  - Uses the system policy to decide access permission
- If the operation is not permitted, the S.M. throws *SecurityException*
  - in some cases, this might be dangerous…

Why is typing a security feature?

- Sandbox mechanisms all rely on type safety
- Example
  - Unchecked C cast lets code make any system call

```
int (*fp)()     /* variable "fp" is a function pointer          */
...
fp = addr;      /* assign address stored in an integer var   */
(*fp)(n);       /* call the function at this address            */
```

As an excerpt from "Concepts in Programming Languages" – Chapter 13

Comparison with C++

- Almost everything is object + Simplicity - Efficiency
  - except for values from primitive types
- Type safe + Safety +/- Code complexity - Efficiency
  - Arrays are bounds checked
  - No pointer arithmetic, no unchecked type casts
  - Garbage collected
- Interpreted + Portability + Safety - Efficiency
  - Compiled to byte code: a generalized form of assembly language designed to interpret quickly.
  - Byte codes contain type information

Comparison (cont'd)

- Objects accessed by ptr + Simplicity - Efficiency
  - No problems with direct manipulation of objects
- Garbage collection: + Safety + Simplicity - Efficiency
  - Needed to support type safety
- Built-in concurrency support + Portability
  - Used for concurrent garbage collection (avoid waiting?)
  - Concurrency control via synchronous methods
  - Part of network support: download data while executing
- Exceptions
  - As in C++, integral part of language design