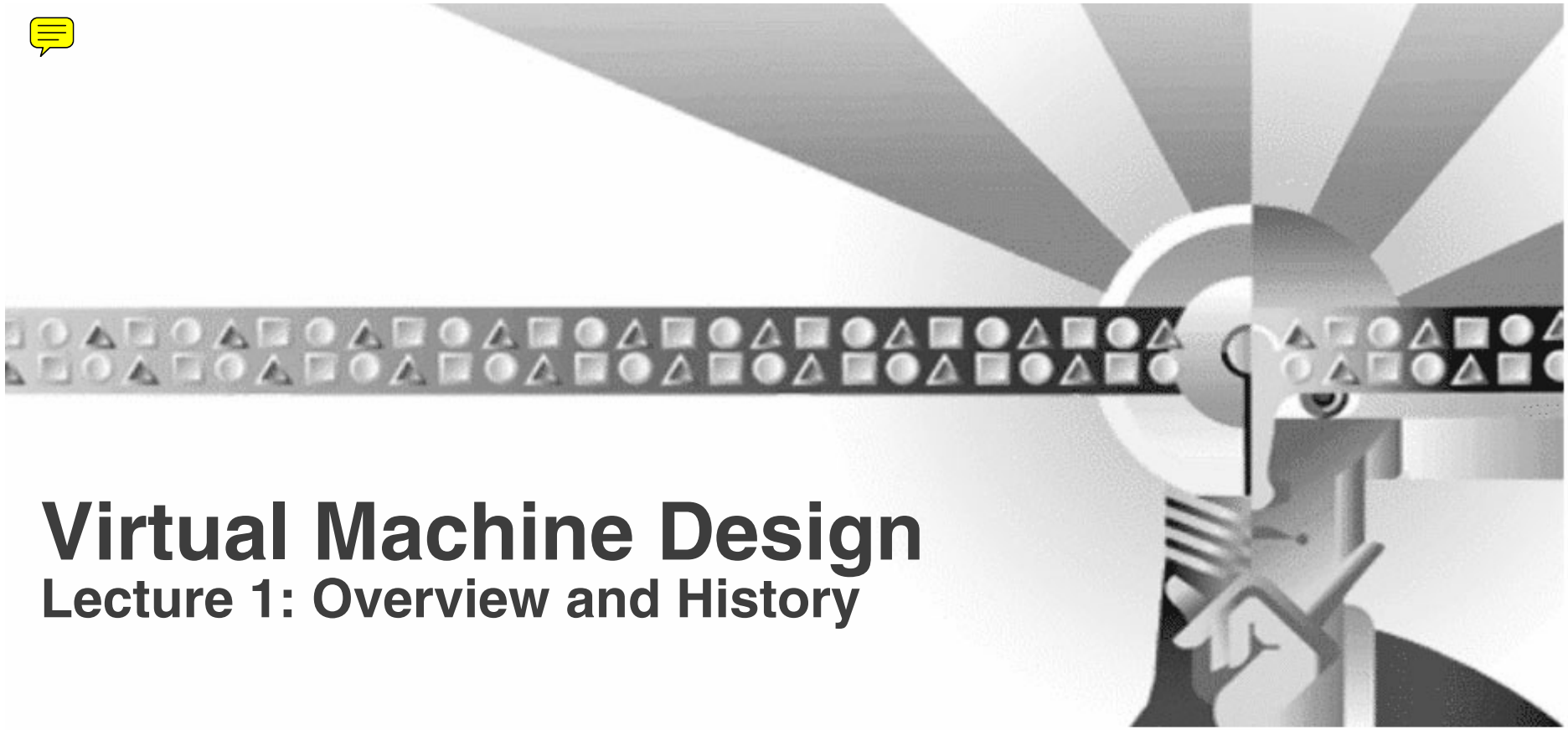


Virtual Machine Design

Lecture 1: Overview and History

Antero Taivalsaari
August 2003

Welcome!

- Welcome to the Virtual Machine Design Seminar.
- TUT seminar 8109035.

==========

- First time a VM design course has been organized in Finland.
- Glad to see that there is so much interest in this topic!

Goals

- Introduce you to the world of virtual machine (VM) design.
- Explain the key technologies that are needed for building virtual machines, such as automatic memory management, interpretation, multithreading, and dynamic compilation.

Structure of the Seminar

- The seminar consists of two parts:
  - Lectures (6 or 7 lectures in total)
  - Student presentations
- Lectures will be held in room TB223 on Wednesdays, 10:15 – 11:45 am.
  - Lecture attendance is not required but recommended.
- To get the credits (2 ov), you must prepare and give a presentation on a selected topic related to virtual machine design.
  - Presentations will begin in November.
  - A list of suggested topics will be available later.

Lecture Schedule (Preliminary)

- Sep 10: History and overview of VM design
- Sep 17: Memory management
- Sep 24: Interpretation and execution
- Oct 1: Multithreading, synchronization and I/O
- Oct 8: Internals of the Java virtual machine

  (Oct 15: No lecture)

  (Oct 22: No lecture)
- Oct 29: High performance VMs (guest lecture)
- Nov 5: Student presentations begin

About the Lecturer

- Built virtual machines since the mid-1980s.
  - Main interests in the 1980s/early 1990s:
    Forth, Smalltalk, Self, other “dynamic” OO languages.
- In 1997, moved to California to work on Java virtual machines at Sun Microsystems.
  - Wrote the K Virtual Machine (KVM) at Sun Labs in 1998.
  - KVM became the starting point for Java 2 Micro Edition (J2ME), a popular version of the Java platform for mobile devices.
- Engineering manager of the J2ME/KVM virtual machine team at Java Software, 1999-2001.
  - Led early J2ME standards activities (CLDC 1.0/1.1)
  - Co-author of the first Java Series book on J2ME.

Introduction

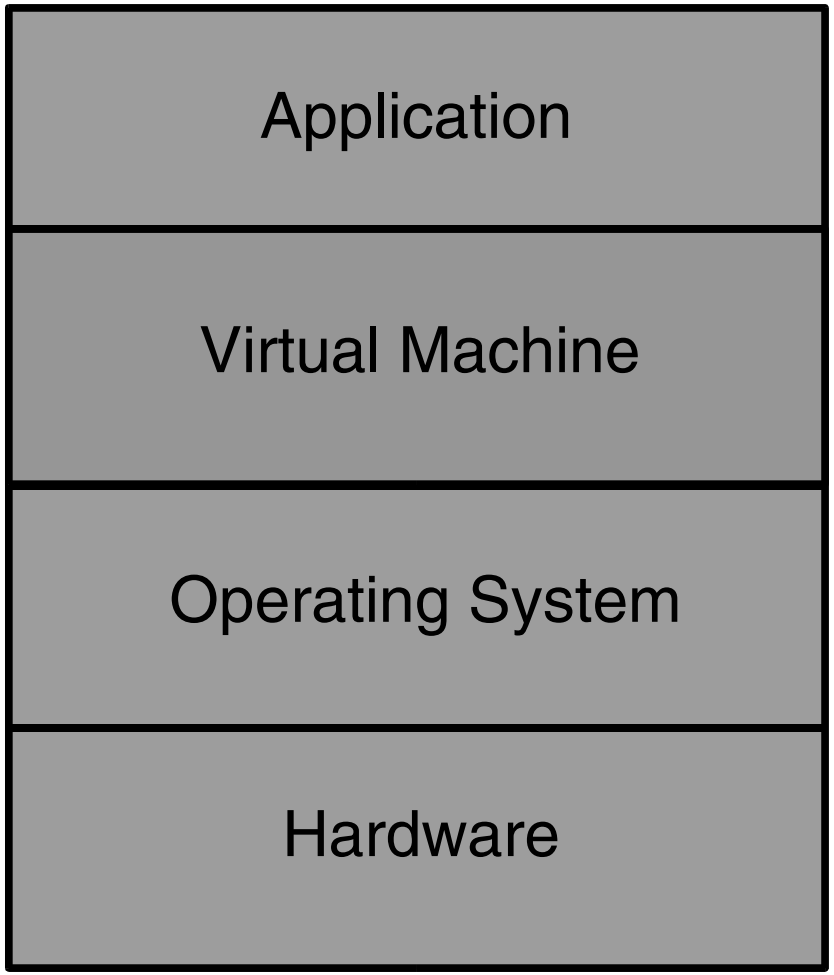
What is a Virtual Machine?

- A *virtual machine* (VM) is an “abstract” computing architecture or computational engine that is independent of any particular hardware or operating system.
- “ Software machine” that runs on top of a real hardware platform and operating system.
- Allows the same programs to run “virtually” on any hardware for which a VM is available.

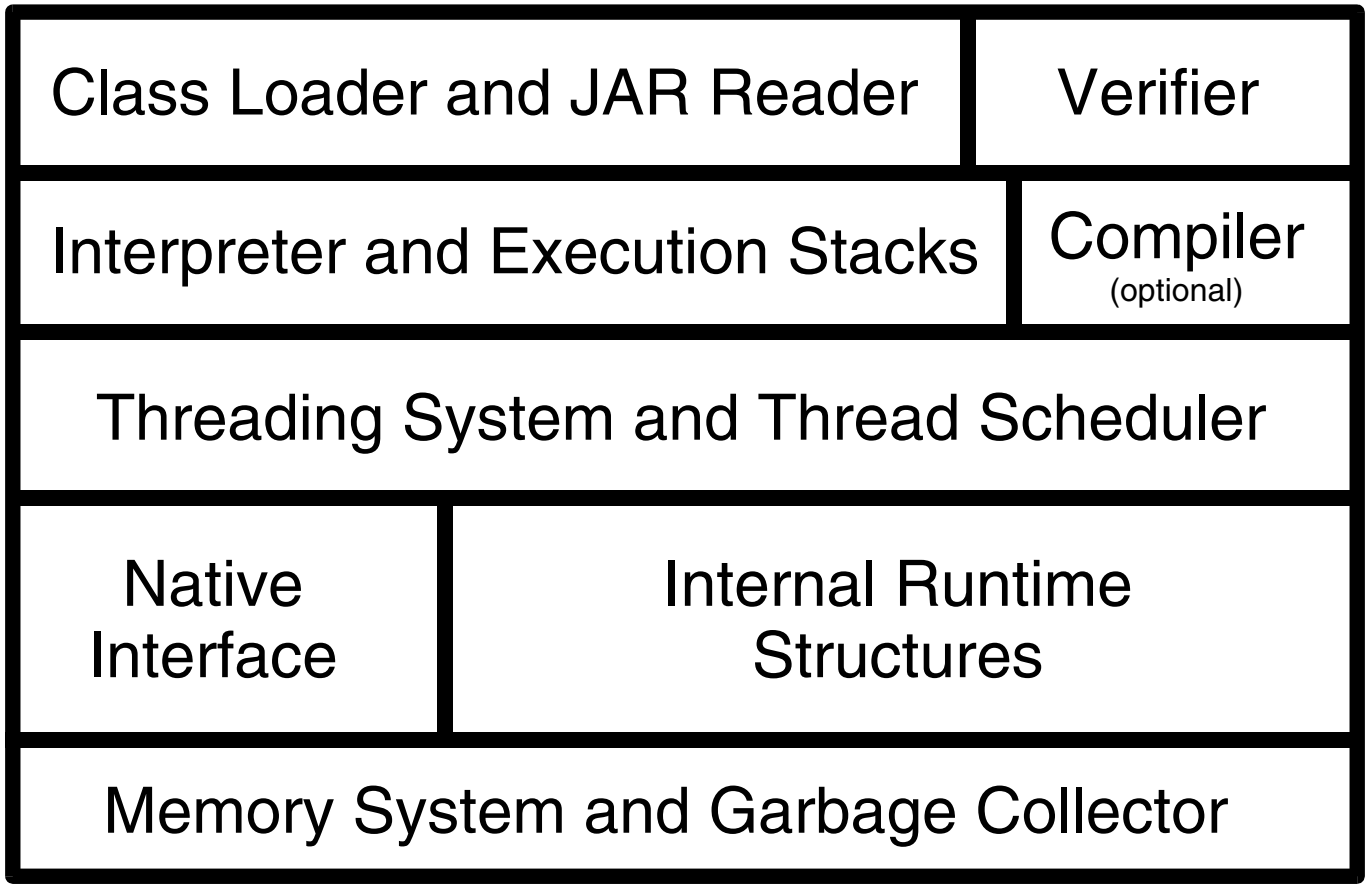
Characteristics of a Virtual Machine

- A virtual machine typically introduces its own instruction set that is used for executing programs.
  - This instruction set is independent of the architecture of the host operating system.
- A virtual machine usually also has its own memory system.
  - Access to the memory system of the host operating system is minimized.
- In general, access to the host operating system is often limited and controlled by the virtual machine's *native function interface*.

Typical High-Level Architecture



Example: Components of a Java Virtual Machine (JVM)



Some Background

- Virtual machines have been studied and built since the late 1950s.
- Many early programming languages were built around the idea of having a portable runtime system.
- Yet VM design was always a fairly specialized topic; not many books or articles were written until recently.
- Popularity of the area exploded in the mid-1990s when the Java programming language was introduced.

Languages that Use Virtual Machines

- Well-known languages using a virtual machine:
  - *Lisp* systems, 1958/1960-1980s
  - *Basic, 1964-1980s*
  - *Forth*, early 1970s
  - *Pascal* (P-Code versions), late 1970s/early 1980s
  - *Smalltalk*, 1970s-1980s
  - *Self*, late 1980/early 1990s
  - *Java*, mid-1990s

- Numerous other languages:
  - ... *PostScript*, *TCL/TK*, *Perl*, *Python*, *C#*, ...

Why are Virtual Machines Interesting?

- Provide platform independence.
- Isolate programs from hardware details.
- Simplify application code migration.
- Can support dynamic downloading of software.
- Can provide additional security that machine-specific implementations cannot provide.
- Can hide complexity of legacy systems.

- Many programming languages are built around a virtual machine.

Virtual Machines vs. Operating Systems

- There is a lot of similarity between VM and OS design.
  - The key component areas are pretty much the same (memory management, multithreading, I/O, ...)
- A few key differences:
  - Virtual machines are usually designed to be as independent of the host operating system as possible.
  - Operating systems are “extensions of the underlying hardware”. They are built to facilitate access to the underlying computing architecture and maximize the utilization of the hardware resources.
  - Also, virtual machines are commonly tied to a particular programming language or language family.
  - Operating systems are usually language-independent.

Existing Material on VM Design

- There is a lot of material available on virtual machines.
- However, the material is scattered/fragmented and it is difficult to find any comprehensive presentations.
- A few books on the topic:
  - Bill Blunden, *Virtual Machine Design and Implementation in C/C++*, Wordware Publishing, March 2002.
  - Ronald Mak, *Writing Compilers and Interpreters*, John Wiley & Sons, July 1996.
- Unfortunately, these books don't cover the area very well.

A Brief History of Programming Languages that Utilize a Virtual Machine

LISP

- John McCarthy, 1958
  - http://www-formal.stanford.edu/jmc/history/lisp/lisp.html
  - LISP is the second oldest programming language still in widespread use (after Fortran)
- LISP is characterized by the following ideas:
  - Computing with symbolic expressions rather than numbers,
  - representation of symbolic expressions and other information by list structure,
  - composition of functions as a tool for forming more complex functions out of a few primitive operations,
  - the representation of LISP programs as LISP data, and the function *eval* that serves both as a formal definition of the language and as an interpreter.

Sample Lisp Code

```
(define (primes)
        (letrec ((sieve (lambda (s)
          (cons (car s)
                  (delay (sieve (filter
                    (lambda (n)
        (> (remainder n (car s)) 0))
                  (force (cdr s)))))))))
        (sieve (force (cdr nat)))))
```

Why is Lisp Interesting from VM Designer's Viewpoint?

- The first language to widely use garbage collection as a means of automating memory management.
- The first language to use recursion extensively.
- One of the first truly interactive languages that didn't require a “compile-link-execute-crash-debug” cycle.
- Lisp was one of the first systems where programs run in a “sandbox”; access to the operating system is limited and programs cannot really crash the system.
- The first truly “reflective” programming language as well; LISP has a very small language core; the rest of the system can be written in itself; programs can be manipulated as data.

UCSD Pascal

- The Pascal language was developed by Nicklaus Wirth in 1969.
- A fairly “conventional” programming language.
  - Predecessor to a large family of other languages (Modula..., Oberon...)
- Pascal did not become popular until Ken Bowles of the University of California San Diego (UCSD) implemented the *P-Code system* in the late 1970s.
  - A portable pseudocode system/language runtime.
  - http://www.threedee.com/jcm/psystem/
  - The P-Code system made the implementation extremely portable, increasing the popularity of Pascal rapidly.

Sample Pascal Code

```
PROGRAM Fibonacci(input,output);
VAR
  lo : INTEGER; hi : INTEGER; n : INTEGER;
  golden_ratio : DOUBLE; ratio : DOUBLE;
BEGIN
  golden_ratio := (1.0 + sqrt(5.0))/2.0;
  lo := 1; hi := 1; n := 1;
  WHILE hi > 0 DO
  BEGIN
    n := n + 1; ratio := hi / lo;
    WRITELN(n : 2, ' ', hi, ratio : 25, ' ', (ratio - golden_ratio) : 21 : 18);
    hi := lo + hi; lo := hi - lo
  END
END
```

Why is UCSD Pascal Interesting from VM Designer's Viewpoint?

- The P-Code system popularized the idea of using *pseudocode* to improve portability of programming language runtime systems.
- Uses a stack-oriented instruction set and five virtual registers.
  - Only one stack (no separate operand & call stacks)
- The first virtual machine implementation widely available to hobbyists.
  - Especially the Apple II implementation was very popular.
  - http://homepages.cwi.nl/~steven/pascal/book/10pcode.html
  - http://www.wikipedia.org/wiki/P-Code_machine

P-Code Sample Instructions

Inst.	Stack before	Stack after	Description
ADI	i1 i2	i1+i2	add two integers
ADR	r1 r2	r1+r2	add two reals
DVI	i1 i2	i1/i2	integer division
INN	i1 s1	b1	set membership; b1 = whether i1 is a member of s1
LDCI	i1	i1	load integer constant
MOV	a1 a2		move
NOT	b1	~b1	boolean negation

BASIC

- Beginners All-purpose Symbolic Instruction Code.
- Developed by John Kemeny and Thomas Kurtz at Dartmouth College (USA) in mid-1960s.
  - http://www.kbasic.org/1/history.php3
- Interactive nature made it suitable for mini- and microcomputers (good timing!)
- Paul Allen and Bill Gates wrote the first interpreted implementation in 1975; this improved the portability of the language dramatically.

Sample BASIC Code

```
100 INPUT “Type a number”; N
120 IF N <= 0 GOTO 200
130 PRINT “Square root=” SQR(N)
140 GOTO 100
200 PRINT “Number must be > 0”
210 GOTO 100
```

Why is BASIC Interesting from VM Designer's Viewpoint?

- It really isn't very interesting...
  - The language has no specific contributions except ease of learning and ease of use.
  - Excessive use of GOTOs led to some horrible programs.
- However, the popularity of BASIC coincided with the microcomputer boom.
  - Many early microcomputer companies decided to integrate BASIC in their products.
  - You could either program in assembly language or BASIC...
- Some BASIC systems used pretty interesting intermediate code representation techniques.

Forth

- Invented by Charles Moore in the early 1970s.
  - http://www.forth.com/Content/History/History1.htm
- Originally designed to control radiotelescopes.
- Characteristics:
  - Forth is a “word-oriented” programming language; there is no syntax or grammar in the traditional sense.
  - All the primitive functions/words are also language keywords; open stack used for parameter passing.
  - Forth makes subroutine definition extremely cheap; this provides for extensibility and high level of procedural abstraction.
  - Extreme minimalism: The entire Forth system (including a simple multitasking programming environment) can fit in 8-15 kilobytes.

Sample Forth Code

```
: xReverse          \ reverse the horizontal direction of the ball
        xStep @ +/- xStep ! ;
: yReverse          \ reverse the vertical direction of the ball
        yStep @ +/- yStep ! ;
: checkLeft         \ check for the left edge of the screen
        x @ 1 <= IF xReverse THEN ;
: checkRight        \ check for the right edge of the screen
        x @ xMax >= IF xReverse THEN ;

ASCII o CONSTANT "ball"

: showBall          \ draw the ball on the screen
        "ball" xyPlot ;
: hideBall          \ hide (undraw) the ball
        "bl" xyPlot ;
: tryBall           \ test the ball drawing routines
        BEGIN
          showBall
          checkLeft checkRight checkTop checkBottom
          hideBall xyStep
        AGAIN ;
```

Why is Forth Interesting from the VM Designer's Viewpoint?

- One of the easiest virtual machines to build.
- The VM consists of a small number of distinct components (stacks, dictionary, interpreter, virtual registers, primitives); no extra “fat”.
- The language itself is small, simple and efficient, and provides an unusual combination of high-level abstraction and very low level programming capabilities.
- High level of reflection (significant portions of the VM written in the language itself.)
- Ideal for embedded systems (if the awkward syntax is not exposed to the end user...)

Smalltalk

- Developed by Alan Kay's team at Xerox PARC
  - There are various versions (Smalltalk-72, -76, -80). Smalltalk-80 is the best known.
  - http://users.ipa.net/~dwighth/smalltalk/bluebook/bluebook_imp_toc.html
- Characteristics:
  - The first truly interactive object-oriented programming language (unlike Simula which was a compiler-based system.)
  - Took “everything is an object” and “message passing” metaphors to the extreme.
  - Everything is available for modification, even the VM itself (very high level of reflection.)
  - Even code is treated as objects (*blocks*).
  - The language is very closely coupled with a graphical interface; source code of a program cannot be easily separated from the programming environment.

Sample Smalltalk Code

```
| aString vowels |
aString := 'This is a string'.
vowels := aString select: [:aCharacter | aCharacter isVowel].

================================

| rectangles aPoint |
rectangles := OrderedCollection
  with: (Rectangle left: 0 right: 10 top: 100 bottom: 200)
  with: (Rectangle left: 10 right: 10 top: 110 bottom: 210).
aPoint := Point x: 20 y: 20.
collisions := rectangles select: [:aRect | aRect containsPoint: aPoint].
```

Why is Smalltalk Interesting From the VM Designer's Viewpoint?

- Various implementation challenges:
  - Everything can be changed on the fly.
  - No static type system.
  - Even numbers are objects that are manipulated by message passing (= arithmetic operations can be slow.)
  - Blocks (heap-allocated code objects/stack frames) are difficult to implement efficiently.
- Extremely interactive/reflective => fun.
- Well-designed and mature class libraries => easy to write interesting software.
- There are high-quality public domain Smalltalk implementations available.
  - http://www.squeak.org/

Self

- Invented by David Ungar and Randall Smith at Xerox PARC and Stanford University in 1986-1987.
  - The majority of the actual implementation work was done at Sun Labs in the 1990s.
  - http://www.sunlabs.com/self
- Prototype-based flavor/variant of Smalltalk.
  - Took the “everything is an object” metaphor even further than Smalltalk.
  - No more classes; objects can inherit (“delegate”) behavior directly from each other.
  - Extremely dynamic language: even the control structures or the inheritance relationships of objects can be changed on the fly.

Sample Self Code

```
acc: bankAccount copy.
acc balance: 100.
b: [acc deposit: 50].
acc balance.            "returns 100"
b value.
b value.
acc balance.            "returns 200"
```

Why is Self Interesting from VM Designer's Viewpoint?

- The Self language is so extremely dynamic that the implementors had to push the limits of VM technology very aggressively:
  - Adaptive compilation to speed up execution.
  - Generational garbage collection (originally invented by David Ungar in his Ph.D. work.)
  - Dynamic deoptimization to allow debugging of highly optimized programs.
  - Novel collaborative / visual programming and debugging environment (tightly integrated with the VM.)
- Many of the key technologies that are used today in mainstream Java virtual machines were invented by the Self group.

Java

- Developed by James Gosling's team at Sun Microsystems in the early 1990s.
  - http://java.sun.com/people/jag/green
- Originally designed for programming consumer devices (as a replacement of C++).
  - Uses a syntax that is familiar to C/C++ programmers.
  - Uses a portable virtual machine that provides automatic memory management and a simple stack-oriented instruction set.
  - *Class file verification* was added to enable downloading and execution of remote code securely.
- Again, great timing: the development of the Java technology coincided with the widespread adoption of web browsers in the mid-1990s.

Sample Java Code

```
class Peg {
    int pegNum;
    int disks[ ] = new int[64];
    int nDisks;

    public Peg(int n, int numDisks) {
        pegNum = n;
        for (int i = 0; i < numDisks; i++) {
            disks[i] = 0;
        }
        nDisks = 0;
    }

    public void addDisk(int diskNum) {
        disks[nDisks++] = diskNum;
    }

    public int removeDisk() {
        return disks[--nDisks];
    }
}
```

Why is Java Interesting from VM Designer's Viewpoint?

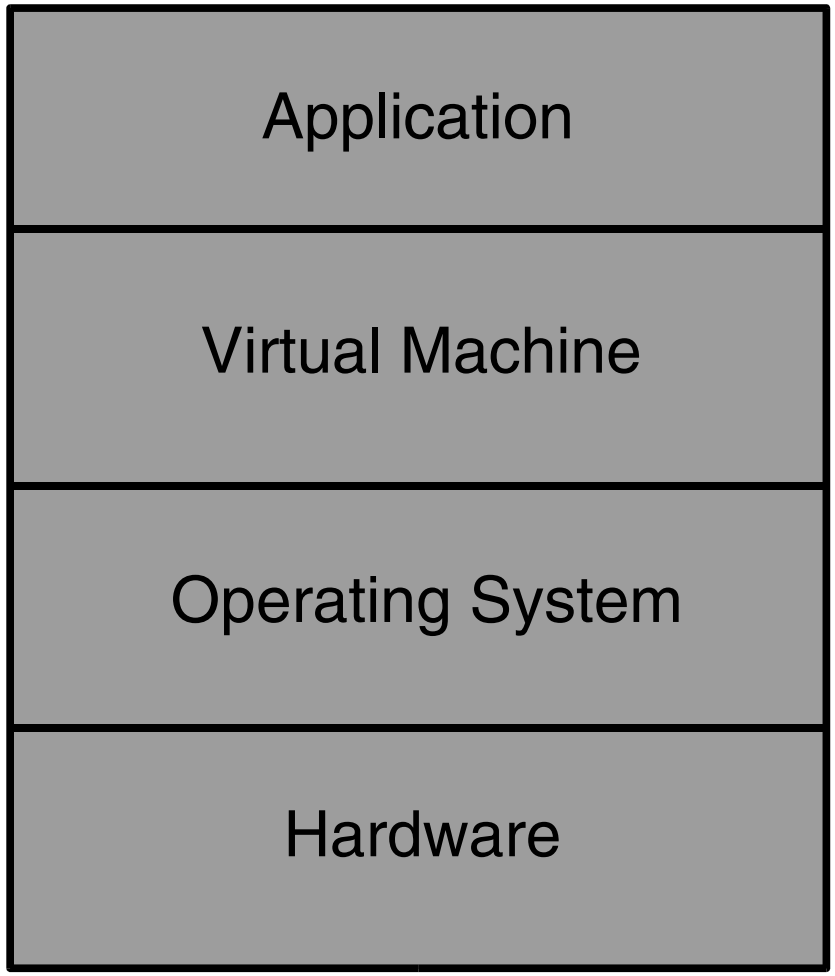
- Most people had never heard of virtual machines until Java came along!
- Combines a statically compiled programming language with a dynamic virtual machine.
- The Java virtual machine (JVM) is very well documented.
  - Tim Lindholm, Frank Yellin, *The Java Virtual Machine Specification*, Second Edition, Addison Wesley, Java Series, April 1999.
- A JVM is seemingly very easy to build.
- However, tight compatibility requirements make the actual implementation very challenging.
  - Must pass tens of thousands of test cases to prove compatibility.

Designing Virtual Machines

How are Virtual Machines Implemented?

- Virtual machines are typically written in “portable” and “efficient” programming languages such as C or C++.
- For performance-critical components, assembly language is used.
  - The more machine code is used, the less portability.
- Some virtual machines (Lisp, Forth, Smalltalk) are largely written in the language itself.
  - These systems have only a minimal core implemented in C or assembly language.
- Most Java VM implementations consist of a mixture of C/C++ and assembly code.

Typical High-Level Architecture



Virtual Machine Design Considerations

- Size
- Portability
- Performance
- Memory consumption
- Scalability
- Security
- ...

There are always trade-offs in VM design!

Virtual Machine Design Considerations

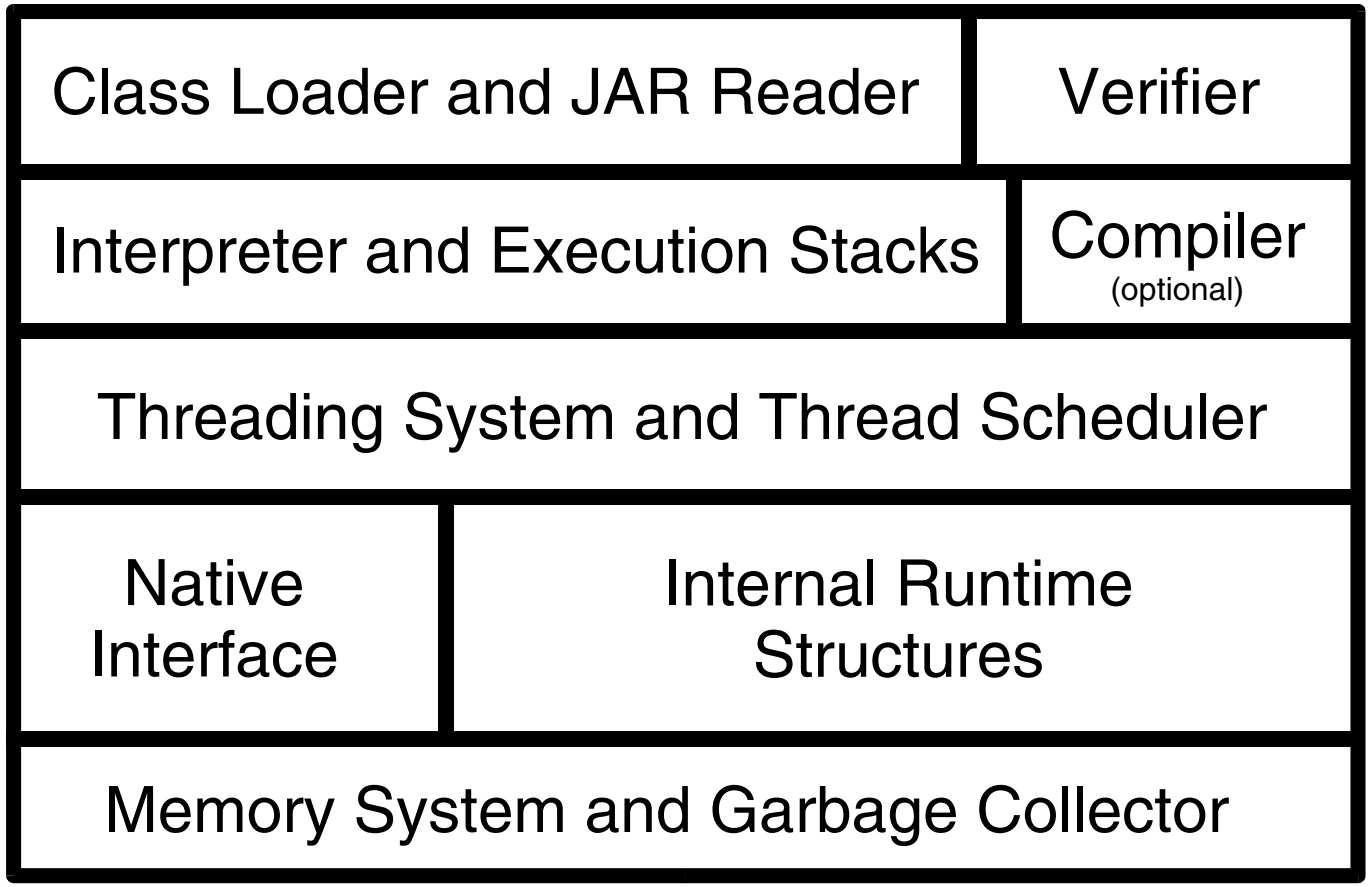
- Unfortunately, for nearly all aspects of the VM:
  - Simple implies slow
  - Fast implies more complicated
  - Fast implies less portable
  - Fast implies larger memory consumption

  – Examples:
    - Interpretation
    - Memory management
    - Locking/Synchronization
    - Dynamic compilation

Components of a Virtual Machine

- The components of a virtual machine vary considerably depending on various factors:
  - Is the language interactive (Smalltalk, Forth) or non-interactive (Pascal, Java)?
  - Does the language have reflection capabilities (can you inspect or modify the VM or the program while it is running)?
  - Does the VM need to have performance that is comparable to non-interpreted systems?
  - Is multithreading support required?
  - Is the VM required to run in a “sandbox”?

Example: Components of a Java Virtual Machine (JVM)



Case Studies

Three Very Different Virtual Machines

- Ruka: A minimal, portable Forth virtual machine.
- KVM: A Java virtual machine implementation intended for small devices.
- Squeak: A feature-rich public domain Smalltalk implementation.

Ruka: A Portable Forth VM

- Written in ANSI C.
- 5,000 lines of code.
- Minimal executable size about 17 KB.

- Like all Forth systems, allows interactive definition and inspection of functions, and provides unrestricted access to the underlying operating system.
- Ported onto various small devices (Palm OS, PocketPC, SymbianOS, ...).

KVM: A Java VM for Small Devices

- Written in ANSI C.
- Version 1.0.4: about 35,000 lines of quite well-commented code.
  - About 50,000 lines if debugging support, native functions for the J2ME CLDC 1.0 libraries, and some network protocol primitives are added.
- Fully compliant with the J2ME CLDC test suite.
- Minimal executable size about 70 KB.
- Ported onto numerous commercial mobile phones all over the world.

http://wwws.sun.com/software/communitysource/j2me/cldc/download.html

Squeak: A Public Smalltalk VM

- A complete, compact implementation of the Smalltalk-80 Specification.
- Includes a very rich graphical programming environment and class library.
- The core VM is about 35,000 lines of C code.
- A complete executable with all the graphics libraries and plug-ins is about 1 MB.

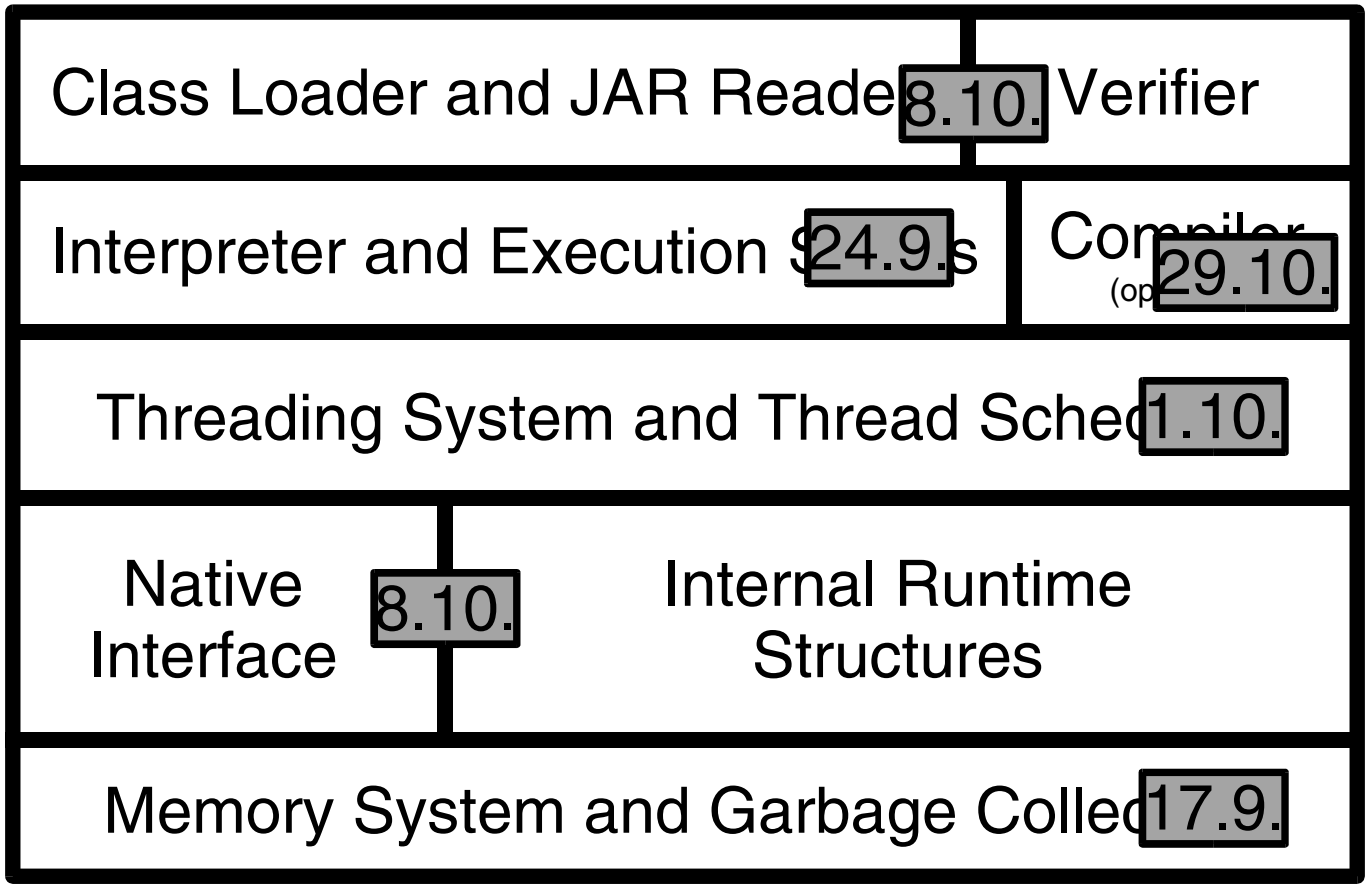
- Various ports available.

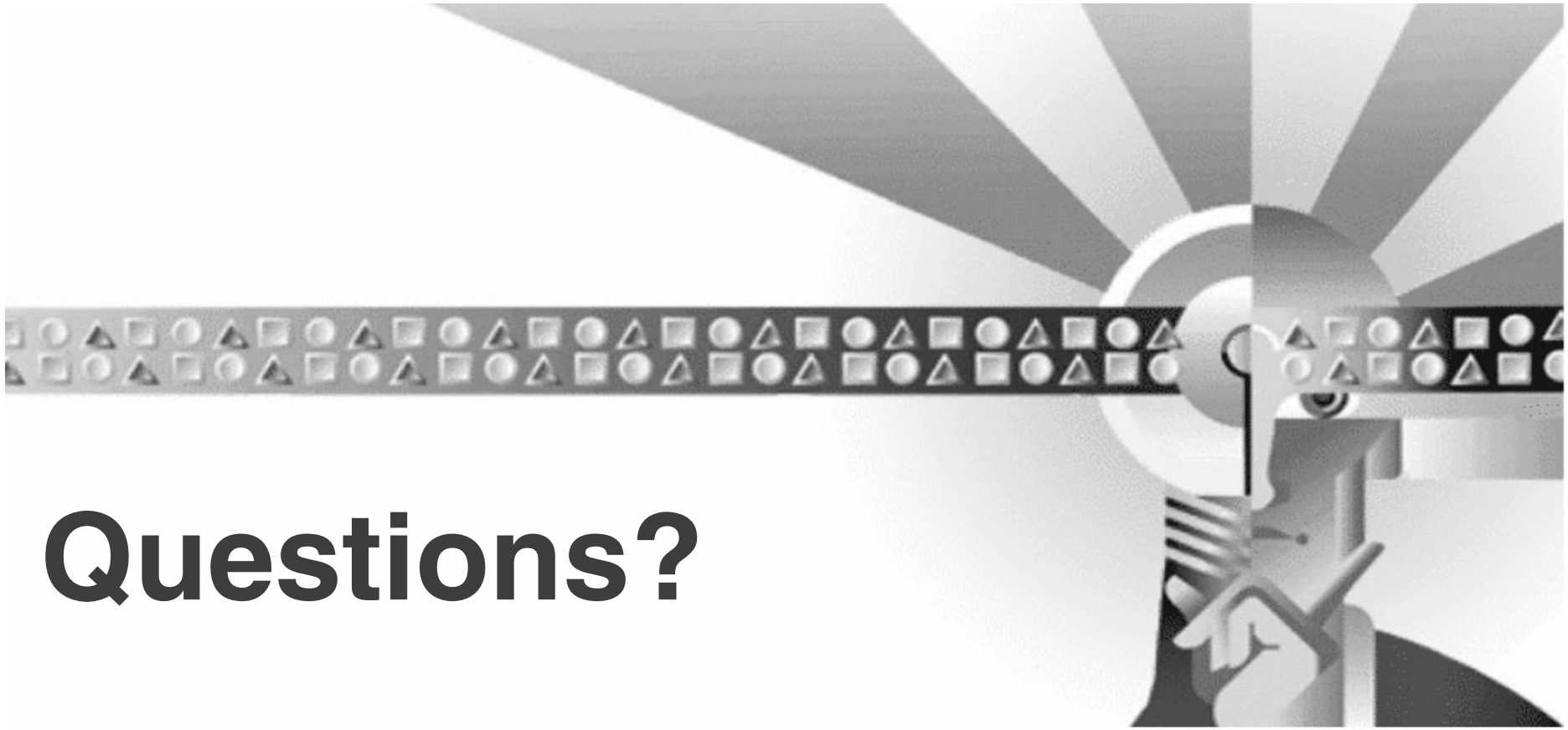
  http://sourceforge.net/projects/squeak/

More Information

- Virtual machine design:
  - Bill Blunden, *Virtual Machine Design and Implementation in C/C++*, Wordware Publishing, March 2002
- Designing “small memory” software:
  - James Noble, Charles Weir, *Small Memory Software*, Addison-Wesley, 2001
- Conferences and workshops:
  - ACM SIGPLAN Workshop on Interpreters, Virtual Machines and Emulators (co-organized with PLDI Conference), June 2003.
  - Usenix Java Virtual Machine Research and Technology Symposium (2001, 2002, 2004)

Forthcoming Lectures





Questions?

Sun microsystems

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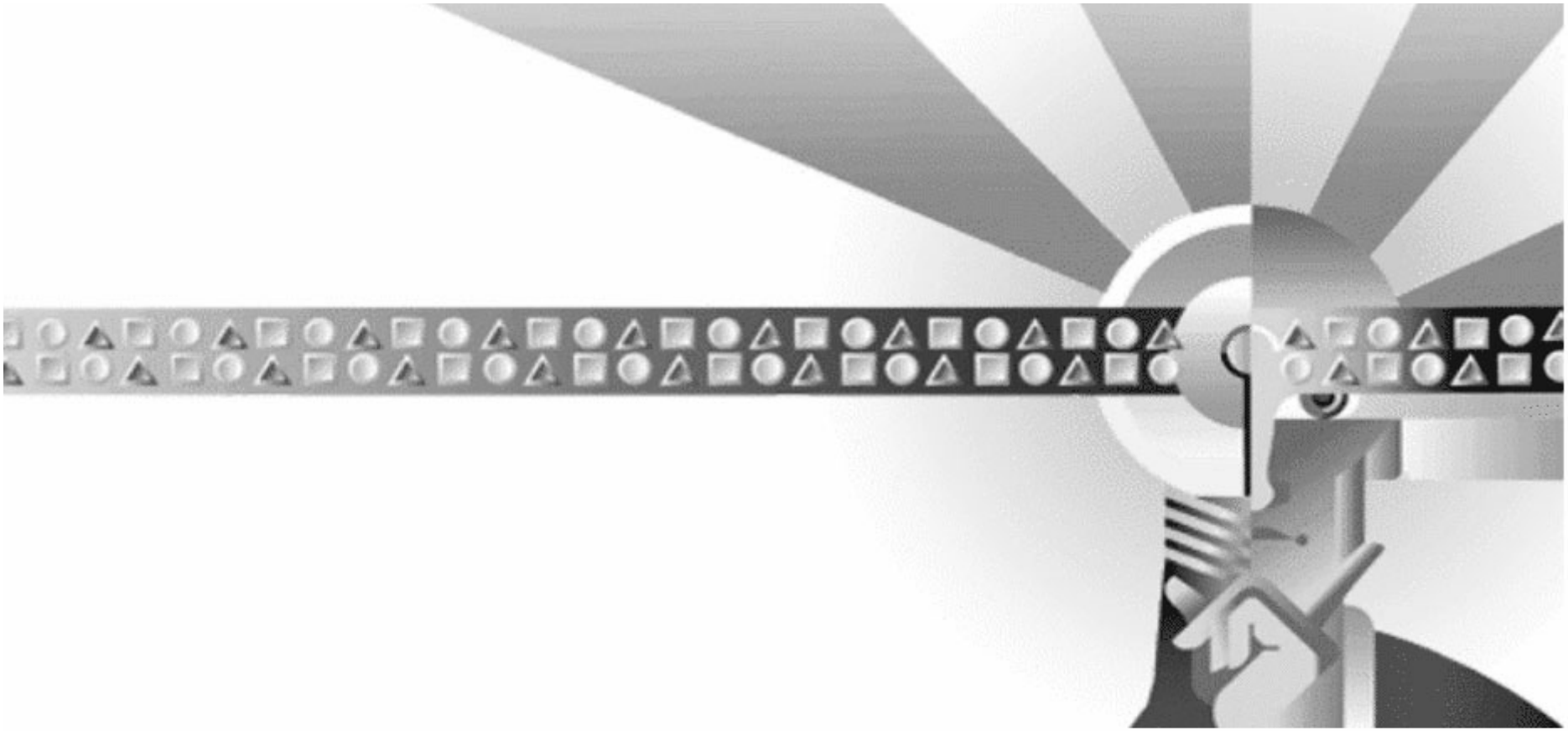

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