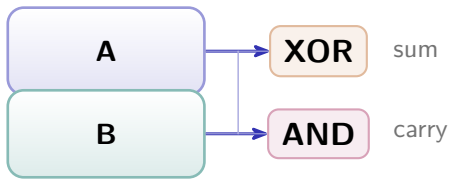
Hardware and Virtual Machines

A-Level Computer Science ▪ Topic 15

A-Level Computer Science



What we will cover

1. RISC vs CISC & pipelining
2. Flynn's taxonomy & parallelism
3. Virtual machines
4. Boolean algebra & K-maps
5. Adders & flip-flops
6. Recap

1 RISC vs CISC

Two styles of CPU design

CISC

复杂指令集

many, often complex instructions

variable length – decoding is intricate

many instructions touch memory

more work per instruction

e.g. Intel x86

RISC

精简指令集

few, simple instructions

fixed length – fast to decode

only *load* and *store* touch memory

each instruction is quick and predictable

e.g. ARM, RISC-V

The comparison that the exam wants

Feature	CISC	RISC
Instruction set	many	few
Instruction length	variable	fixed
Memory access	many instructions	only load/store
Pipeline-friendly	harder	naturally
Cycles per instruction	varies	usually 1

The trade-off is doing more per instruction (CISC) vs doing each one faster and more predictably (RISC). Modern Intel chips translate CISC into RISC-like micro-ops.

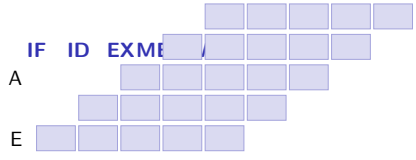
Pipelining – an assembly line for instructions

A **pipeline** 流水线 processes instructions in overlapping stages:

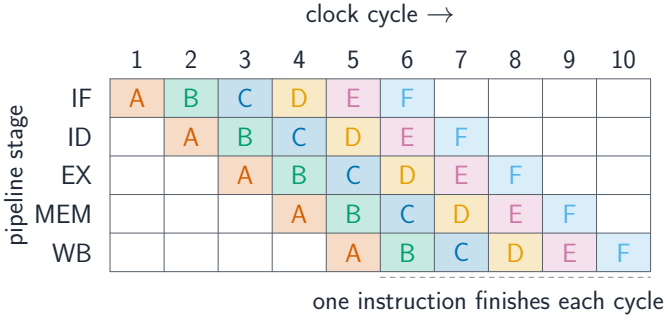
Fetch → Decode → Execute → Memory → Write back

Once the pipeline is full, one instruction completes per cycle. RISC's fixed-length, simple instructions make every stage take the same time.

A pipeline **hazard** 冒险 stalls it: a *data* hazard (result not ready) or a *control* hazard (a branch makes the next address unknown).



Pipelining overlaps the stages of six instructions



Each instruction still takes the same time; what changes is that one finishes every cycle instead of every four. A branch empties the pipeline and the gain is lost until it refills.

2

Parallelism

Flynn's taxonomy

Flynn's taxonomy 弗林分类 sorts computers by instruction streams × data streams.

SISD

one instruction, one data stream – a traditional single core

SIMD

one instruction on *many* data items – GPUs, vector units

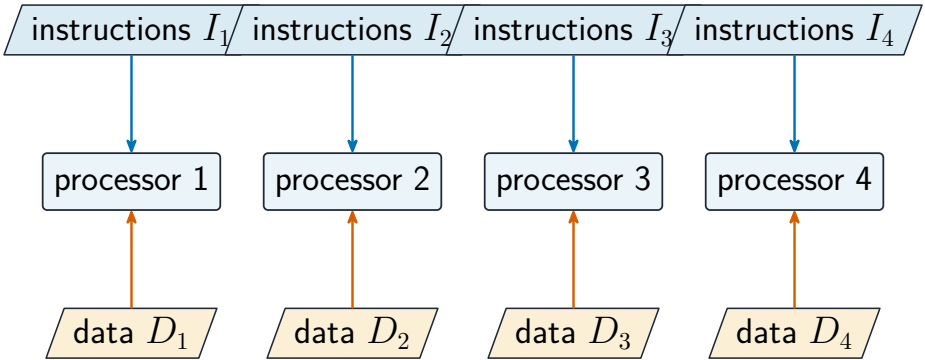
MISD

several operations on the same data – rare, mostly theoretical

MIMD

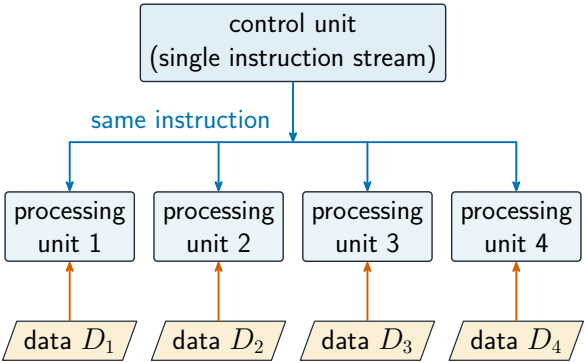
many processors, different instructions on different data – multi-core, clusters

MIMD: own instructions, own data



MIMD: each processor runs its own instructions on its own data

SIMD: one instruction, many data

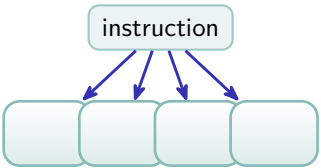


SIMD: many processors run the same instruction on different data

SIMD vs MIMD, in pictures

SIMD

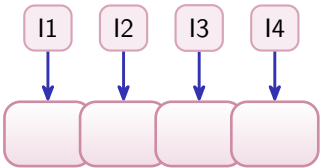
one instruction, many data



a graphics card: thousands of cores, same op on many pixels

MIMD

many instructions, many data

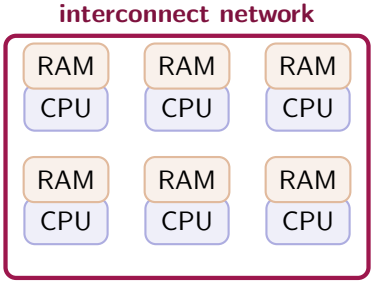


multi-core CPUs and clusters

Massively parallel computers

A **massively parallel** 大规模并行 system uses thousands of processors on a fast network.

- each has its **own memory**: **distributed memory** 分布式内存
- they exchange data by **messages**; it is **MIMD**
- needs specially written software (MPI, CUDA)



Climate simulation, large **machine learning** 机器学习 training, astrophysics.

3 Virtual machines

Two kinds of virtual machine

A **virtual machine** 虚拟机 is a software emulation of a whole computer – the software inside sees a CPU, memory and disks that look real.

system VM

runs a complete OS

a **hypervisor** 虚拟机监控器 creates and manages VMs

uses: different OSes on one machine; server consolidation; **sandboxing** 沙箱; snapshots

process VM

runs one program in portable **bytecode** 字节码

JVM, CLR, CPython

write once, run anywhere; runtime safety; **JIT** 即时编译

cost: an extra layer

4 Boolean algebra

Laws you must be able to use

Boolean algebra 布尔代数 simplifies expressions. + is OR, · is AND, an overbar is NOT.

Law	Form
identity	$A + 0 = A, \quad A \cdot 1 = A$
null	$A + 1 = 1, \quad A \cdot 0 = 0$
idempotent	$A + A = A$
inverse	$A + \overline{A} = 1, \quad A \cdot \overline{A} = 0$
De Morgan 德摩根定律	$(A + B)' = A' \cdot B', \quad (A \cdot B)' = A' + B'$
absorption 吸收律	$A + AB = A$

Example: $Z = AB + A\overline{B} = A(B + \overline{B}) = A$. Fewer terms $\Rightarrow$ fewer gates.

Boolean algebra, and where it runs

Truth tables	**Truth tables** 真值表 list every input combination with its output – the definitive way to prove two expressions equivalent.
De Morgan's laws	**De Morgan's laws** 德摩根定律: $\overline{A \cdot B} = \overline{A} + \overline{B}$ and $\overline{A + B} = \overline{A} \cdot \overline{B}$ – break the bar and swap the operator.
The ALU	The **ALU** 算术逻辑单元 is where these gates end up: it performs the arithmetic and logic the instruction set exposes.
Just-in-time compilation	**Just-in-time compilation** 即时编译 compiles bytecode to native code *while* the program runs, so hot paths get compiled and the rest is interpreted.

Simplify with the laws, then check with a truth table. The check costs four rows and catches every algebra slip.

Karnaugh maps – group the 1s

A **Karnaugh map** 卡诺图 simplifies by grouping adjacent 1s.

- rows and columns in **Gray code** 格雷码 $(00, 01, 11, 10)$
- groups are rectangles whose sides are 1, 2, 4, 8
- the map wraps around its edges
- a group of 2 drops one variable; of 4 drops two

1s in $\overline{A}B$ and AB

The two 1s share the $B = 1$ column. A changes, so it disappears:

$$X = B$$

Two gates fewer than $\overline{A}B + AB$.

5 Adders and flip-flops

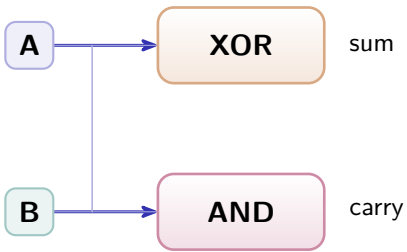
Half adder – two bits, no carry-in

A **half adder** 半加器 adds two bits A and B:

$$S = A \text{ XOR } B, \qquad C = A \text{ AND } B$$

It ignores any carry-in – hence "half".

A	B	S	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

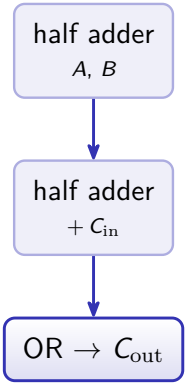


Full adder – three bits, including carry-in

A **full adder** 全加器 adds A, B and a carry-in:

$$S = A \text{ XOR } B \text{ XOR } C_{\text{in}}$$

Built from two half adders plus an OR gate. Chain them (each carry-out feeds the next carry-in) to make a multi-bit *ripple-carry* adder.



Flip-flops – one bit of memory

A **flip-flop** 触发器 is a **bistable** 双稳态 circuit: two stable states, so it remembers one bit. Building block of registers and SRAM.

SR

SR 触发器

S sets $Q = 1$; R resets $Q = 0$

$S = 0, R = 0$ holds

$S = 1, R = 1$ is invalid

two cross-coupled NOR gates

JK

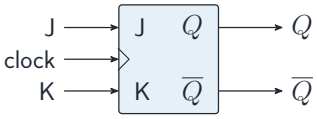
JK 触发器

$J = 1, K = 1$ is a **toggle** 翻转

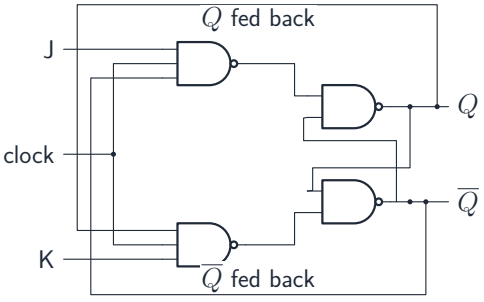
ideal for **counters** 计数器

usually *clocked* – inputs act on a clock edge

Flip-flops – one bit of memory, in detail



block symbol



build from NAND gates

A JK flip-flop: its symbol and a build from NAND gates

Pipelining

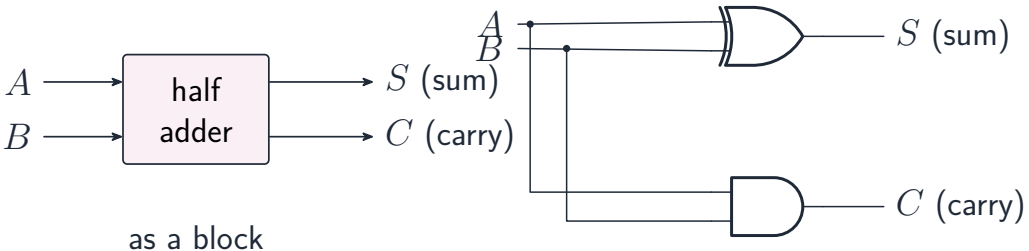
A CPU heat-sink and fan carry heat away from the processor

A GPU: SIMD in hardware

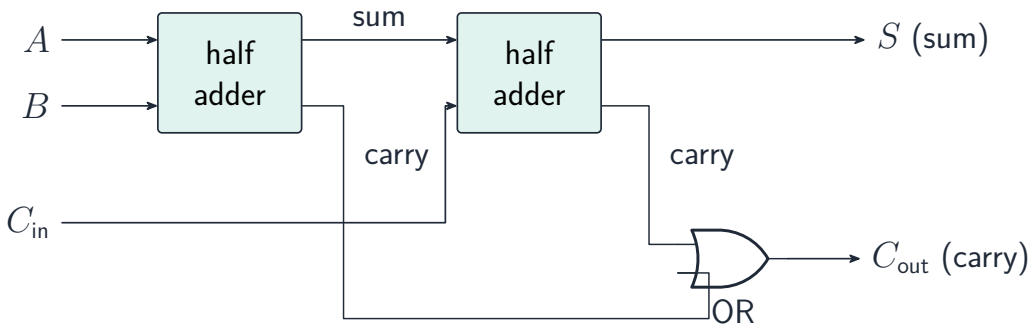
A graphics card: its GPU runs the same instruction on many data items at once (SIMD)

Half adder and full adder

A half adder, as a block and as a circuit of an XOR and an AND gate



A full adder is built from two



A half adder cannot take a carry in, which is why one alone can only add the least significant bit. Chain full adders and the carry ripples along the word.

RISC vs CISC processors

CISC has many complex instructions; RISC has few simple ones

CISC
many, complex instructions
variable length
does more per instruction

RISC
few, simple instructions
fixed length
each instruction is fast

The motherboard that links the parts

A motherboard links the CPU, memory and other parts together

A data centre of server racks

Rows of servers in a data centre, like those used for massively parallel computing

6 Recap

Topic 15 – key takeaways

1 RISC

simple, fixed-length, pipeline-friendly

2 Flynn

SISD, SIMD, MISD, MIMD

3 Logic

De Morgan, K-maps, half vs full adder

4 Memory

flip-flop stores one bit; VMs emulate a computer

Check yourself

1. Why does RISC suit pipelining better than CISC?
2. A GPU running one instruction on many pixels – SISD, SIMD or MIMD?
3. What extra input does a full adder have that a half adder does not?
4. What does $J = 1, K = 1$ do on a JK flip-flop?

Answers **1.** fixed-length, simple stages of equal time **2.** SIMD **3.** carry-in **4.** toggle