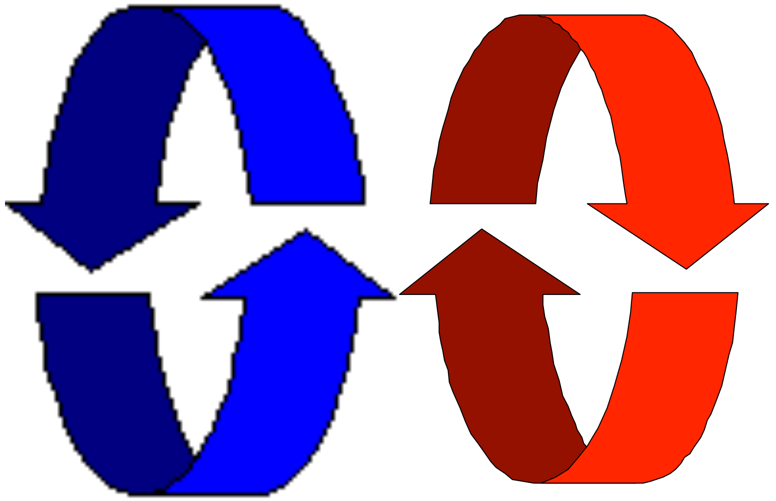
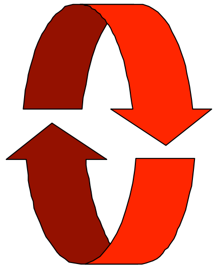
Concurrency

Concepts, Models and Programs

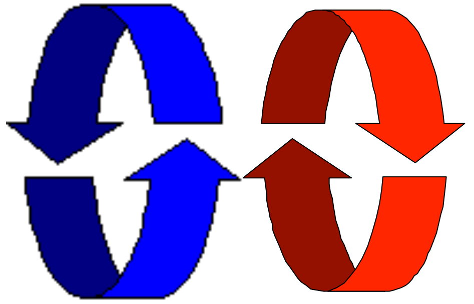


Jeff Kramer and Jeff Magee

What is a Concurrent Program?

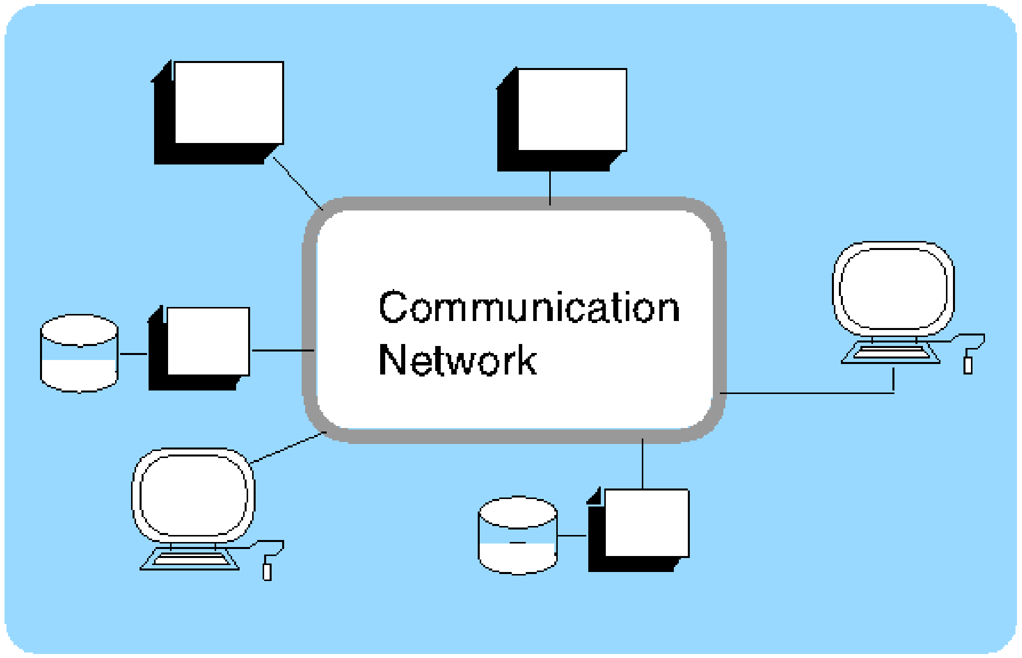


A **sequential** program has a single thread of control.



A **concurrent** program has multiple threads of control allowing it perform multiple computations in parallel and to control multiple external activities which occur at the same time.

Concurrent and Distributed Software?



Interacting, concurrent software components of a system:

single machine -> *shared memory interactions*

multiple machines -> *network interactions*

Why Concurrent Programming?

- Performance gain from multiprocessing hardware
  - eg. fine grain parallelism on multicore hardware : low level memory models
  - eg. coarse grain parallelism for partitioned scientific calculations : processes
- Increased application throughput : avoid polling (busy waiting)!
  - eg. an I/O call need only block one thread
- Increased application responsiveness
  - eg. high priority thread for user requests.
- **More appropriate structure**
  - for programs which interact with the environment, control multiple activities and handle multiple events – coarse grain parallelism.

Concurrency is widespread but error prone!

A very simple example:

- process 1: x := x + 1 (x shared variable)
- process 2: x := x - 1 (x shared variable)

Final result?
Single line instructions are generally **not** atomic.
Assuming read and write are atomic, the result depends on the order of read and write operations on x!

We have a race condition!

Concurrency is widespread but error prone!

There are 4 atomic x-operations:

Process 1 reads x (R1), writes to x (W1).

Process 2 reads x (R2), writes to x (W2).

R1 must happen before W1 and R2 before W2, so these operations can be sequenced in 6 ways (x initially 0):

R1	R1	R1	R2	R2	R2
W1	R2	R2	R1	R1	W2
R2	W1	W2	W1	W2	R1
W2	W2	W1	W2	W1	W1
0	-1	1	-1	1	0

We see that the final value of x is -1, 0, or 1. The program is thus non-deterministic : the result can vary from execution to execution.

Concurrency is widespread but error prone!

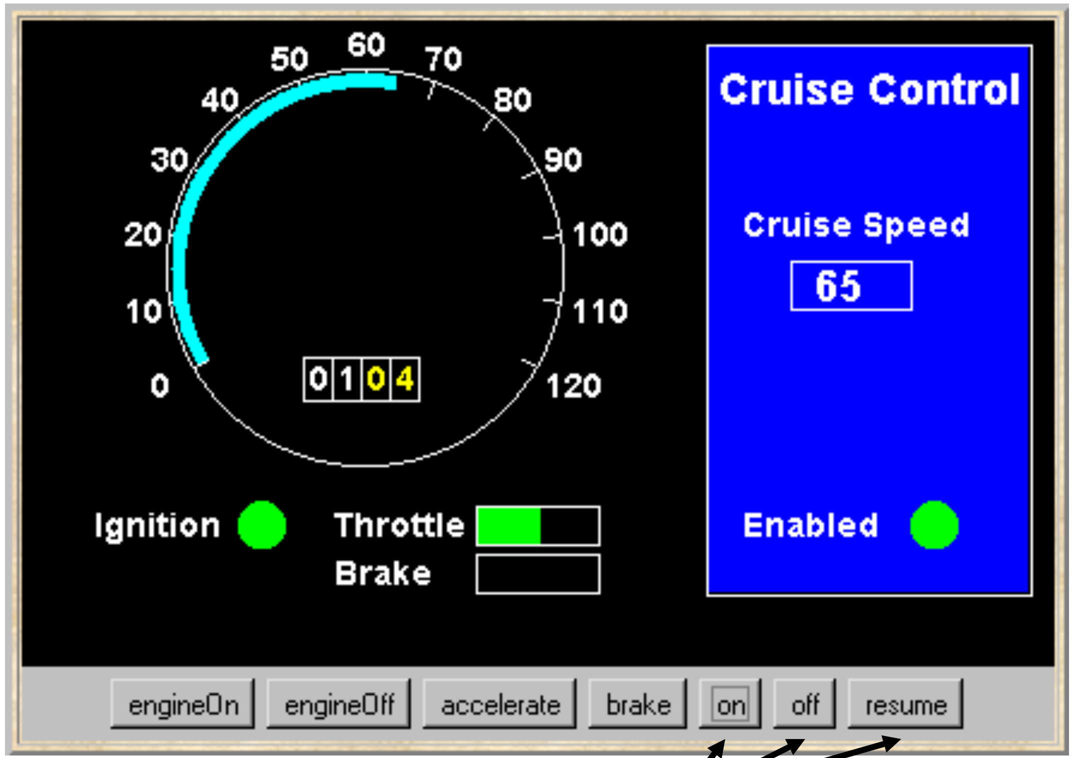
♦ Therac - 25 computerised radiation therapy machine

Concurrent programming errors contributed to accidents causing deaths and serious injuries.

♦ Mars Rover

Problems with interaction between concurrent tasks caused periodic software resets reducing availability for exploration.

a Cruise Control System



buttons

When the car ignition is switched on and the **on** button is pressed, the current speed is recorded and the system is enabled: *it maintains the speed of the car at the recorded setting.*

Pressing the brake, accelerator or **off** button disables the system. Pressing **resume** re-enables the system.

- *Is the system safe?*
- *Would testing be sufficient to discover all errors?*

Models for concurrent programming

Engineering is based on the use of simpler, ***abstract*** *models for experimentation, reasoning and exhaustive analysis.*

Abstraction? definitions …

- the act of withdrawing or removing something
- the act or process of leaving out of consideration one or more properties of a complex object so as to attend to others

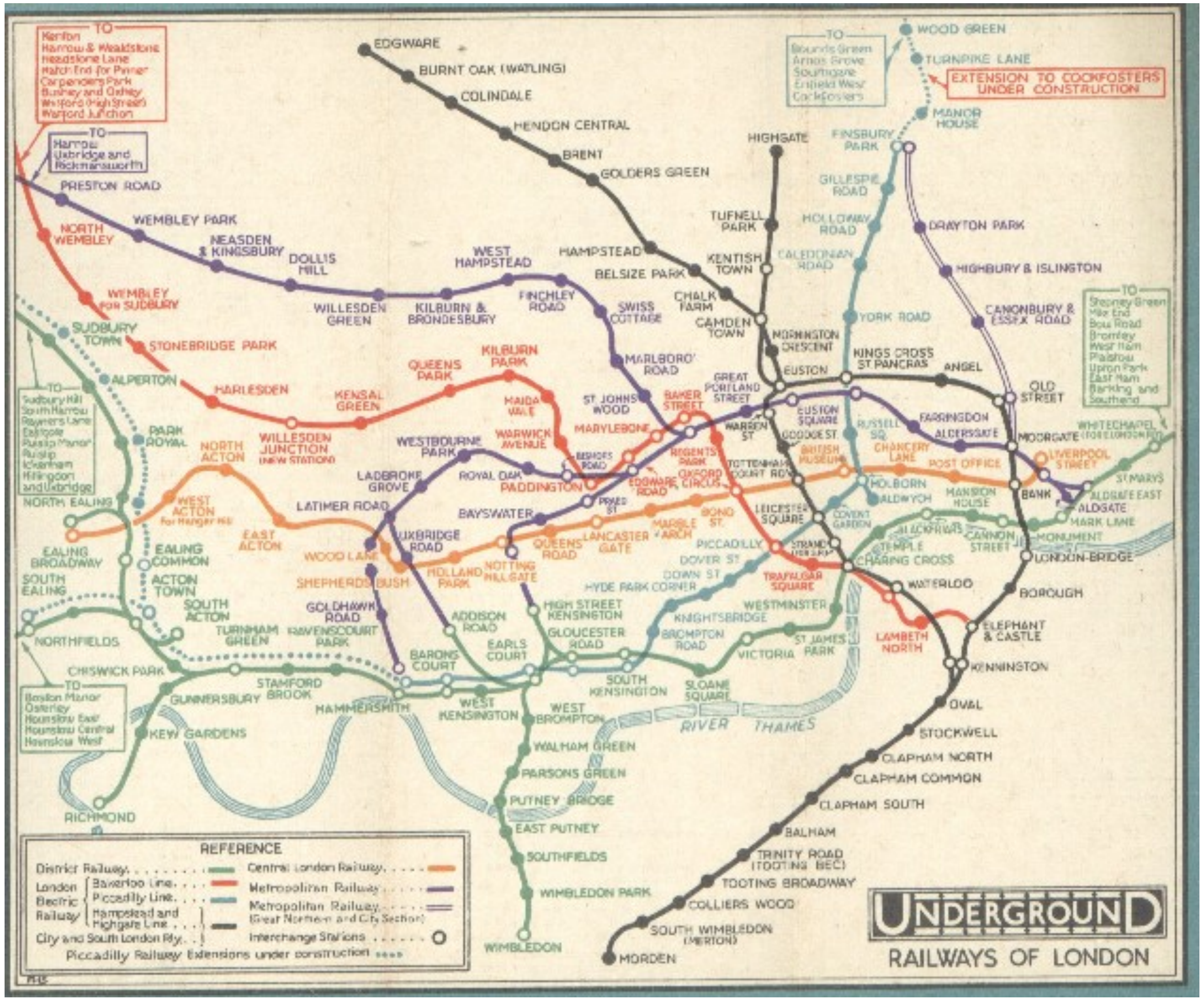
Remove detail (simplify) and

focus (selection based on purpose)

- a general concept formed by extracting common features from specific examples
- the process of formulating general concepts by abstracting common properties of instances

Generalisation (core or essence)

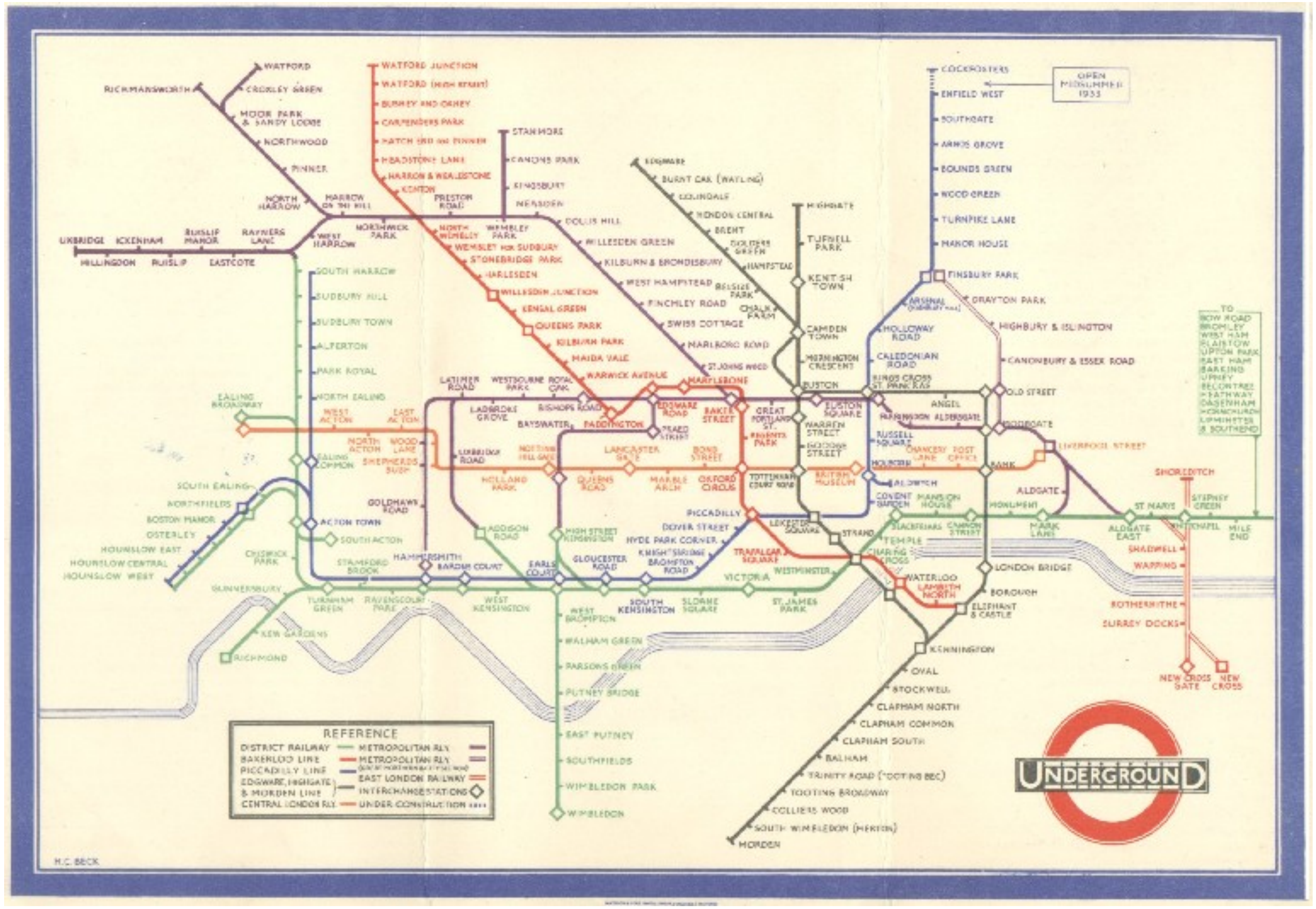
1930 – London Underground map



“Fit for purpose?”

Purpose: relationship between stations and the interchanges, not actual distances.

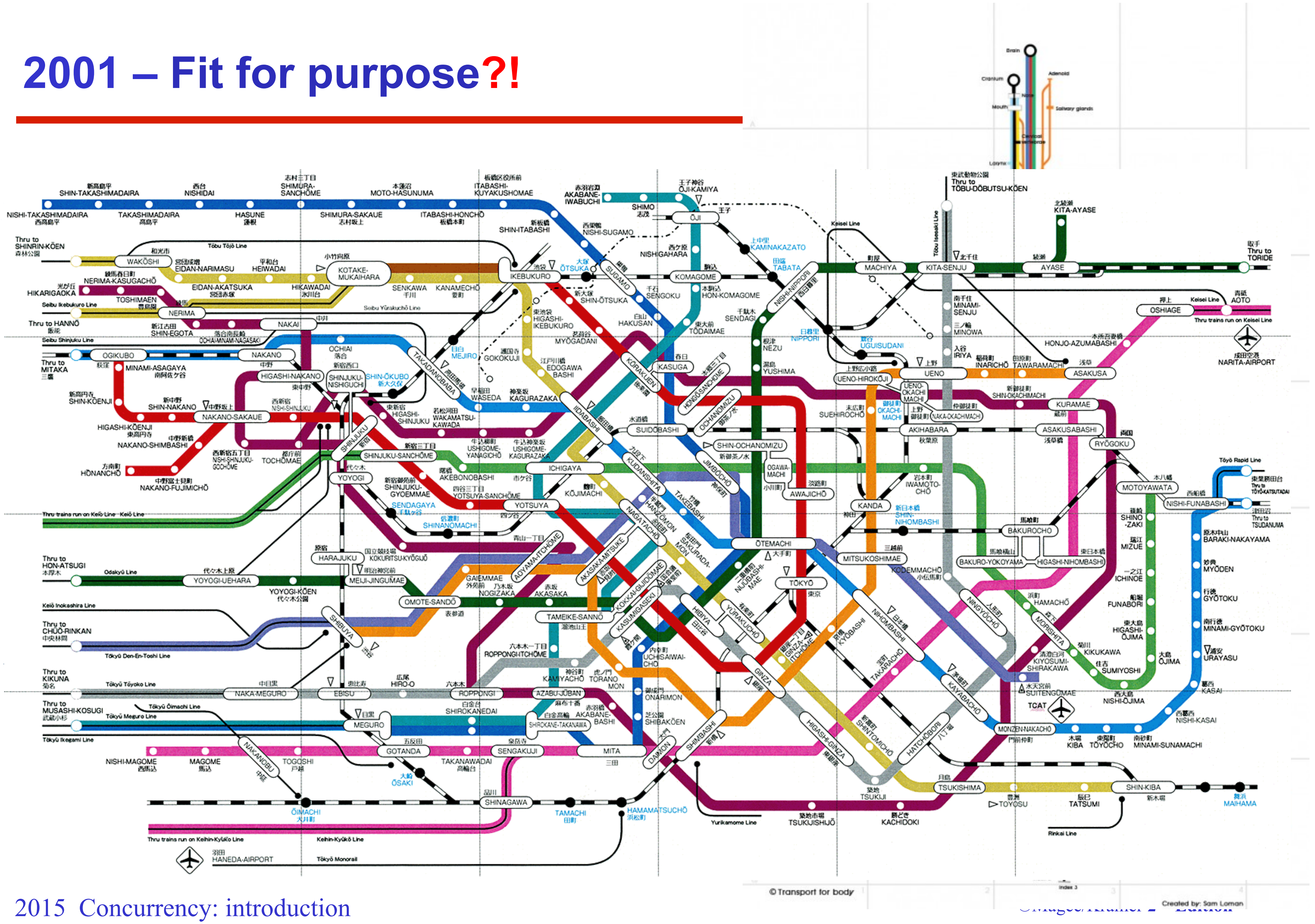
1932 – Harry Beck (1st schematic image map)



2001 – Fit for purpose ("mind the gap…")

Key to lines
Key to symbols
Restricted services
© Transport for London

2001 – Fit for purpose?!



Why is abstraction important in Software Engineering?

Software is abstract!

"Once you realize that computing is all about constructing, manipulating, and reasoning about abstractions, it becomes clear that an important prerequisite for writing (good) computer programs is the ability to handle abstractions in a precise manner."

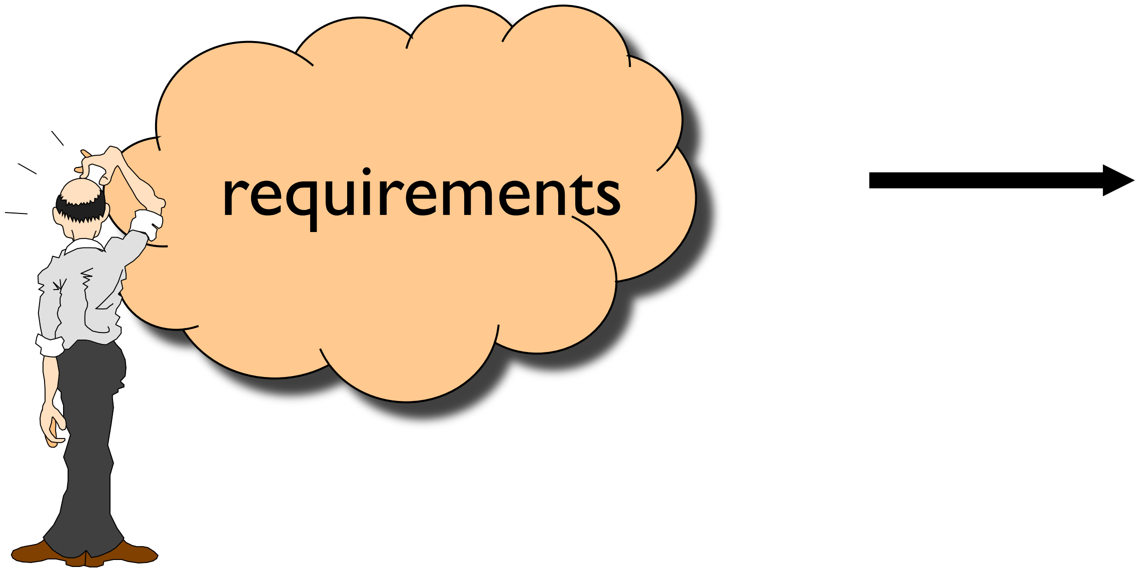
Keith Devlin CACM Sept.2003

Perhaps abstraction is the key to computing …. ?

CACM April 2007

Why is it important? requirements engineering

Requirements - elicit the critical aspects of the environment and the required system while neglecting the irrelevant.



goals
scenarios
assumptions
constraints
properties

"The act/process of leaving out of consideration one or more properties of a complex object so as to attend to others"

Why is it important? design

Design - articulate the software architecture and component functionalities which satisfy functional and non-functional requirements while avoiding unnecessary implementation constraints.

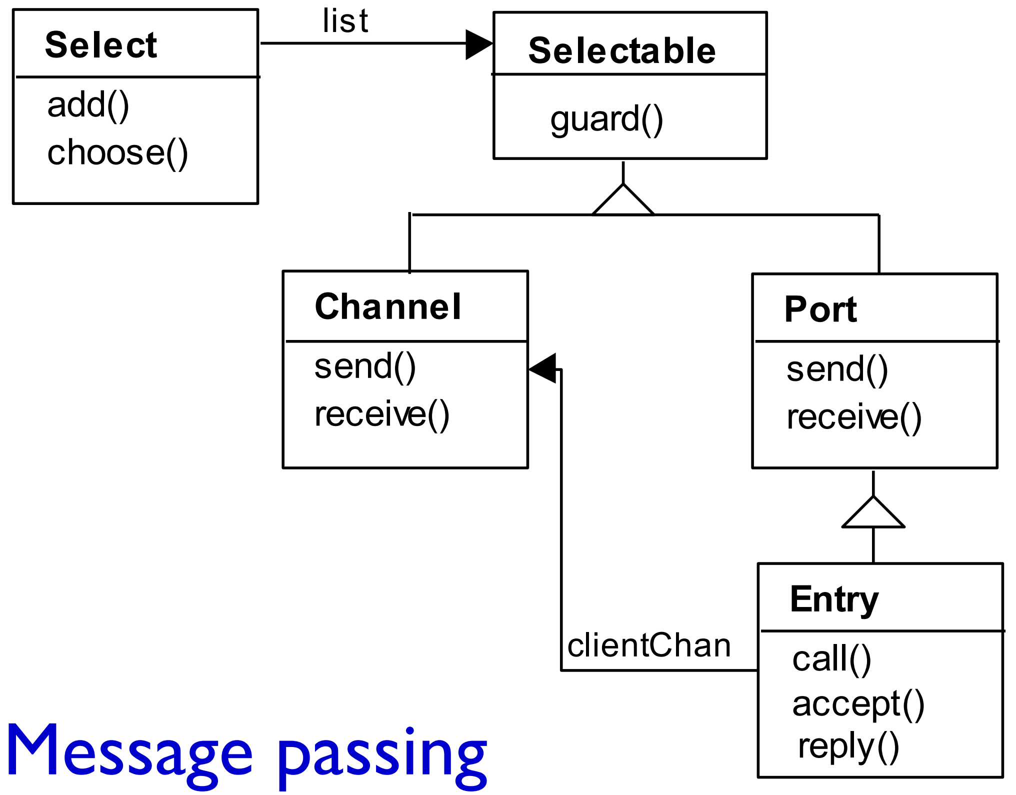
eg. Compiler design (Ghezzi):

- *abstract syntax* to focus on essential features of language constructs;
- design to generate intermediate code for an *abstract machine*

"The act/process of leaving out of consideration one or more properties of a complex object so as to attend to others"

Why is it important? programming

Programming - use data abstraction and classes so as to generalize solutions.



Message passing

"the process of formulating general concepts by abstracting common properties of instances"

Why is it important? advanced topics

Abstract interpretation for program analysis - map concrete domain to an abstract domain which captures the semantics for the purpose at hand.

eg. Rule of signs for multiplication *

0*+ = 0*- = +*0 = -*0 = 0

+*+ = -*- = +

+*- = -*+ = -

Hankin

"the process of formulating general concepts by abstracting common properties of instances"

Models for concurrent programming

*Engineering is based on the use of simpler, **abstract** models for experimentation, reasoning and exhaustive analysis.*

***Abstraction** is fundamental to Engineering in general, and to Software Engineering in particular !*

Models and Model Checking

A model is an abstract, simplified representation of the real world.

Engineers use models to gain confidence in the adequacy and validity of a proposed design:

- ♦ focus on an aspect of interest - concurrency
- ♦ model animation to visualise a behaviour
- ♦ automated model checking of properties (safety & progress)

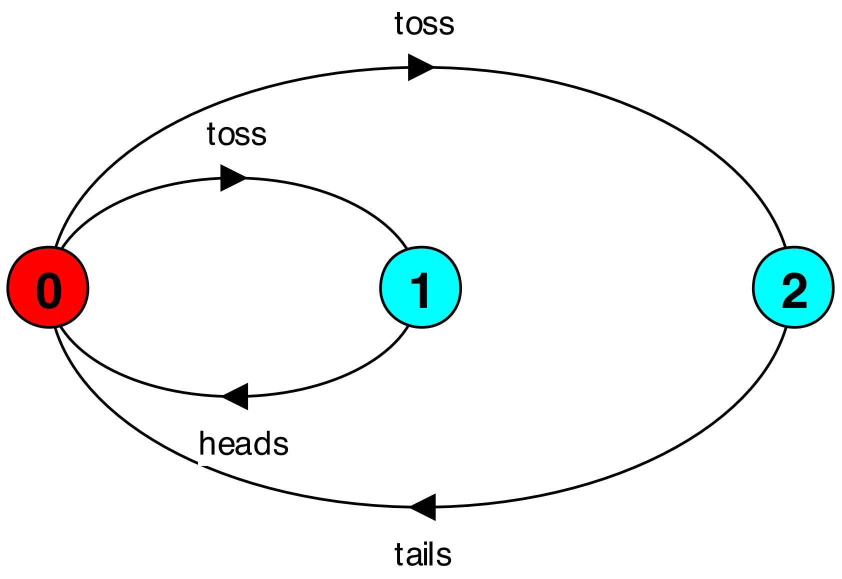
Models are needed to

- ♦ experiment, test, and check a design before it is implemented
  - ♦ airplane software before test flight
  - ♦ net bank services before customer use
  - ♦ medical sensor system before patient use

- ♦ may model an environment, hardware units, partly unknown parts, third party software, …

Models and Model Checking

Models are described using state machines, known as Labelled Transition Systems **LTS**. These are described textually in a Process Algebra as finite state processes (**FSP**) and displayed and analysed by the ***LTSA*** model checking analysis tool.



```
COIN = (toss->HEADS
       |toss->TAILS),
HEADS= (heads->COIN),
TAILS= (tails->COIN).
```

Finite State Machines and Model Checking

Turing awards related to Model Checking

- (2007) Edmund M. Clarke, E. Allen Emerson, Joseph Sifakis:
  - "for their role in developing Model-Checking into a highly effective verification technology that is widely adopted in the hardware and software industries."
- (1996) Amir Pnueli:
  - "For seminal work introducing temporal logic into computing science and for outstanding contributions to program and system verification."
- (1986) John E Hopcroft, "Bob" Tarjan:
  - foundation of formal languages for state machines
- (1976) Michael O. Rabin, Dana S. Scott:
  - Finite Automata and Their Decision Problem, which introduced the idea of nondeterministic machines, which has proved to be an enormously valuable concept.

Process Algebra

Turing awards related to Process Algebra

- (1991) “Robin” Milner:

  For three distinct and complete achievements:

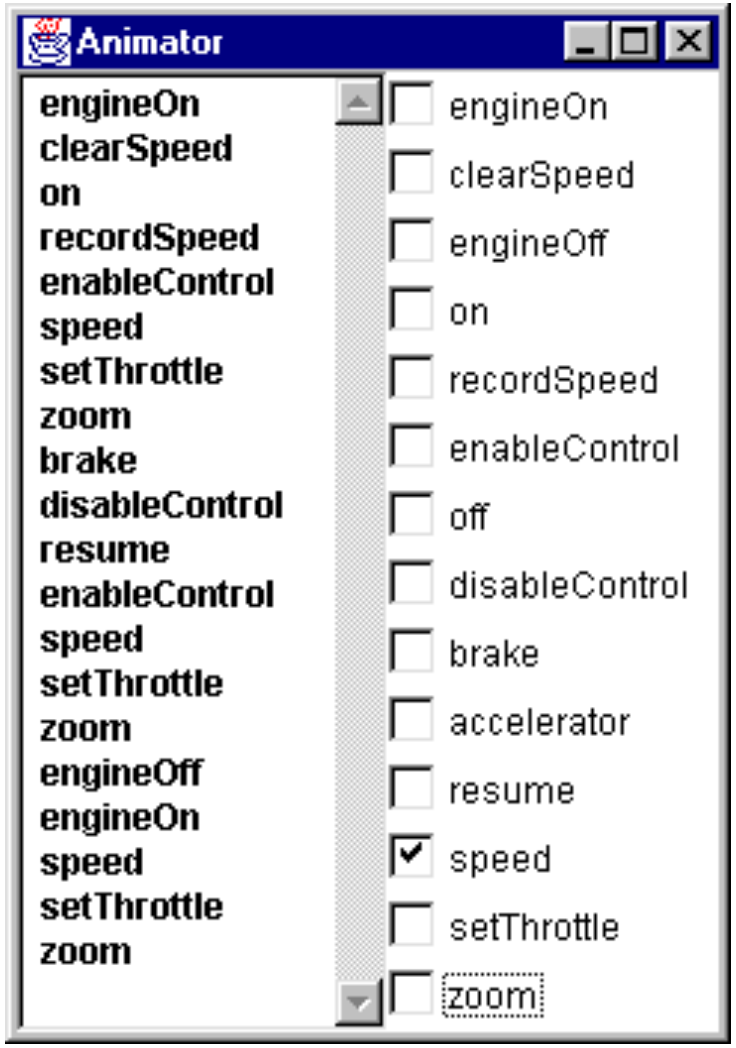
  - LCF the mechanization of Scott’s Logic of Computable Functions, for machine assisted proof construction;
  - ML the first language to include polymorphic type inference together with a type-safe exception-handling mechanism;
  - Process Algebra: CCS (Calculus of Communicating Systems) a general theory of concurrency.

- (1980) “Tony” Hoare.

  For his fundamental contributions to the definition and design of programming languages..”

  - Process Algebra: the language and theory around CSP (Communicating Sequential Processes)

modelling the Cruise Control System



engineOn
clearSpeed
on
recordSpeed
enableControl
speed
setThrottle
zoom
brake
disableControl
resume
enableControl
speed
setThrottle
zoom
engineOff
engineOn
speed
setThrottle
zoom

☐ engineOn
☐ clearSpeed
☐ engineOff
☐ on
☐ recordSpeed
☐ enableControl
☐ off
☐ disableControl
☐ brake
☐ accelerator
☐ resume
☑ speed
☐ setThrottle
☐ zoom

LTSA **Animator to step through system actions and events.**

$$\begin{tikzcd} 0 \arrow[r, bend left, "engineOn"] & 1 \arrow[l, bend left, "engineOff"] \arrow[loop right, "speed"] \end{tikzcd}$$

LTS of the process that monitors speed.

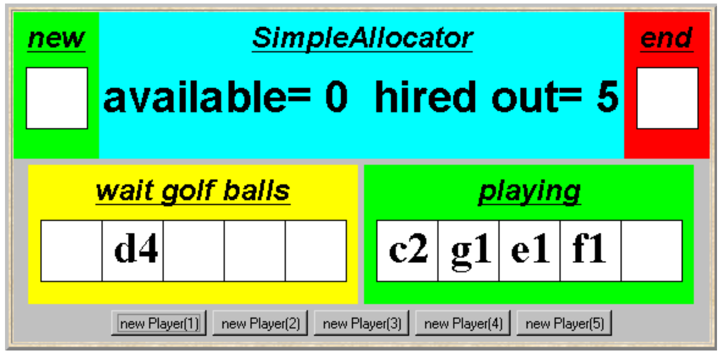
Later chapters will explain how to construct models such as this so as to perform animation and verification.

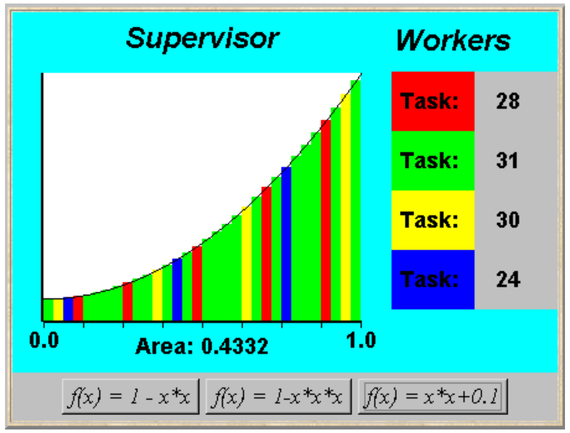
programming practice in Java

Java is

- widely available, generally accepted and portable
- provides sound set of concurrency features

Hence Java is used for all the illustrative examples, the demonstrations and the exercises. Later chapters will explain how to model, check and construct Java programs such as the Cruise Control System and others …





course objectives

This course is intended to provide a sound understanding of the basic ***concepts***, ***models*** *and* ***practice*** involved in designing concurrent software.

The emphasis on principles and **concepts** provides a thorough understanding of the issues and the solutions. **Modelling** provides insight into concurrent behavior and aids reasoning about particular designs. Concurrent programming in **Java** provides the programming **practice** and experience.

Learning outcomes…

After completing this course, you will know

- how to model, analyze, and program concurrent object-oriented systems.
- the most important concepts and techniques for concurrent programming.
- what are the problems which arise in concurrent programming.
- what techniques you can use to solve these problems.

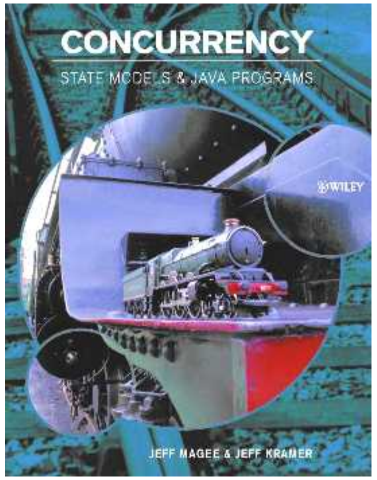
Book

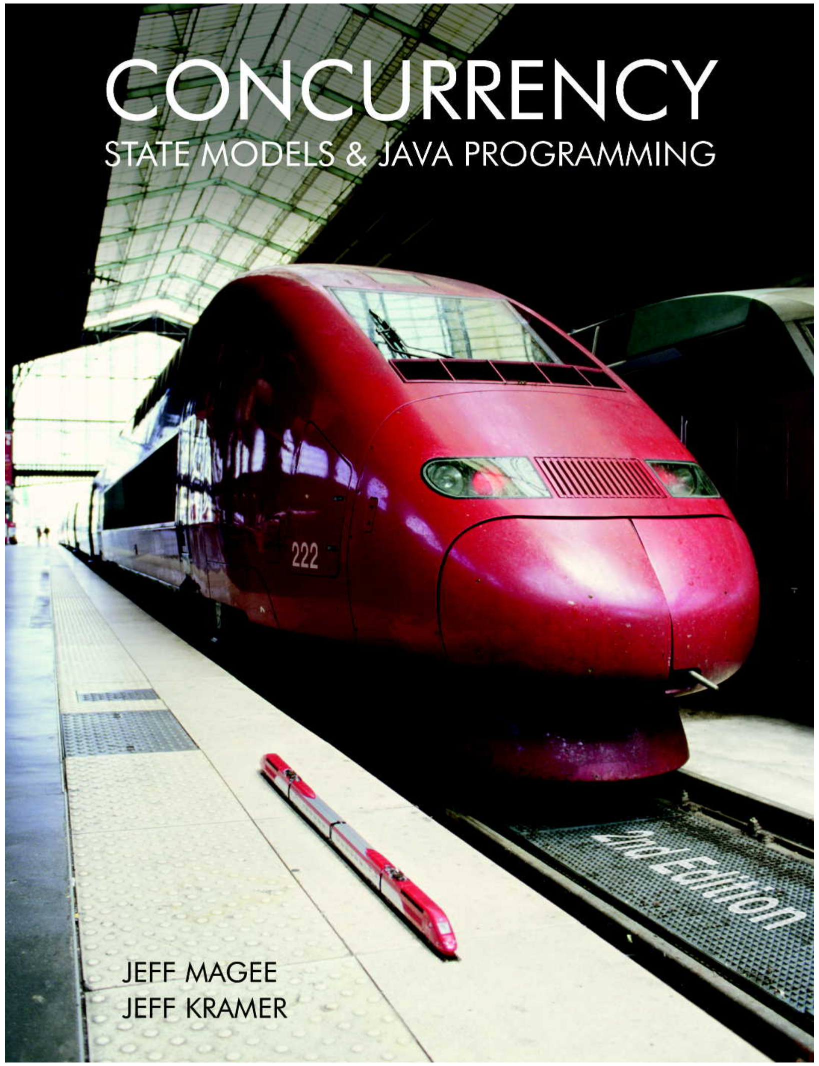
Concurrency: State Models & Java Programs, 2nd Edition

Jeff Magee & Jeff Kramer

WILEY

1st edition





Course Outline

2. **Processes and Threads**
3. **Concurrent Execution**
4. **Shared Objects & Interference**
5. **Monitors & Condition Synchronization**
6. **Deadlock**
7. **Safety and Liveness Properties**
8. **Model-based Design**

The main basic

Concepts

Models

Practice

Advanced topics …

9. Dynamic systems
10. Message Passing
11. Concurrent Software Architectures
12. Timed Systems
13. Program Verification
14. Logical Properties

Web based course material

http://www-dse.doc.ic.ac.uk/concurrency/

- Java examples and demonstration programs
- State models for the examples
- Labelled Transition System Analyser (***LTSA***) for modelling concurrency, model animation and model property checking.

Summary

- Concepts
  - **we adopt a model-based approach for the design, analysis and construction of concurrent programs**
- Models
  - **we use finite state models to represent concurrent behaviour.**
- Practice
  - **we use Java for constructing concurrent programs.**

  Examples are used to illustrate the concepts, models and demonstration programs.