

# Principles and Specifications of Concurrent Systems

Leslie Lamport

Version of 20 August 2015

## The *Principles* and *Specification* Tracks

?

←

→

C

I

S

### 1 Introduction

- 1.1 Concurrent Computation
- 1.2 Modeling Computation
- 1.3 Specification
- 1.4 Systems and Languages

Sections colored like this have  
not yet been written.

### 2 The One-Bit Clock

- 2.1 The Clock's Behaviors
- 2.2 Describing the Behaviors
- 2.3 Writing the Specification
- 2.4 The Pretty-Printed Version of Your Spec
- 2.5 Checking the Specification
- 2.6 Computing the Behaviors from the Specification
- 2.7 Other Ways of Writing the Behavior Specification
- 2.8 Specifying the Clock in PlusCal

### 3 The Die Hard Problem

- 3.1 Representing the Problem in TLA<sup>+</sup>
- 3.2 Applying TLC
- 3.3 Expressing the Problem in PlusCal

### 4 Euclid's Algorithm

- 4.1 The Greatest Common Divisor
  - 4.1.1 Divisors
  - 4.1.2 CHOOSE and the Maximum of a Set
  - 4.1.3 The GCD Operator
- 4.2 Comments
- 4.3 The Algorithm
- 4.4 The TLA<sup>+</sup> Translation
- 4.5 Checking Safety
- 4.6 Checking Liveness
- 4.7 The Translation Revisited
- 4.8 The Grain of Atomicity
- 4.9 Why Euclid's Algorithm Is Correct
  - 4.9.1 Proving Invariance
  - 4.9.2 Verifying  $GCD1-GCD3$

## 5 The Generalized Die Hard Problem

- 5.1 The PlusCal Representation
- 5.2 Checking the Algorithm
- 5.3 The TLA<sup>+</sup> Translation

## 6 Alternation

- 6.1 The Problem
- 6.2 The One-Bit Clock Revisited
- 6.3 Specifying Alternation: Safety
- 6.4 Specifying Alternation: Liveness
- 6.5 The Two-Phase Handshake Protocol
- 6.6 Refinement
- 6.7 Refinement and Stuttering
  - 6.7.1 Adding Steps
  - 6.7.2 Temporal Logic and Stuttering
  - 6.7.3 A Finer-Grained Algorithm
- 6.8 Temporal Logic and Refinement
- 6.9 Alternation Revisited
- 6.10 Round-Robin Synchronization
  - 6.10.1 The One-Bit Clock Revisited Again
  - 6.10.2 An  $N$ -Valued Clock
  - 6.10.3 An Implementation of the  $N$ -Valued Clock
  - 6.10.4 Round-Robin Synchronization

# The *Principles* Track

## 7 Mutual Exclusion

- 7.1 The Problem
- 7.2 The One-Bit Protocol
  - 7.2.1 The Protocol
  - 7.2.2 An Assertional Proof
  - 7.2.3 Using TLC to Check an Inductive Invariant
- 7.3 The Two-Process One-Bit Algorithm
  - 7.3.1 The Two-Process Algorithm
  - 7.3.2 Busy Waiting Versus Synchronization Primitives
  - 7.3.3 Requirement (c)
- 7.4 Proving Liveness
- 7.5 An Informal Proof
- 7.6 A More Formal Proof
- 7.7 The  $N$ -Process One-Bit Algorithm

- 7.8 The Bakery Algorithm
  - 7.8.1 The Big-Step Algorithm
  - 7.8.2 Choosing the Grain of Atomicity
  - 7.8.3 The Atomic Bakery Algorithm
  - 7.8.4 The Real Bakery Algorithm
- 7.9 Mutual Exclusion in Modern Programs

?

## 8 The Bounded Channel and Bounded Buffer

- 8.1 The Bounded Channel
  - 8.1.1 The Specification
  - 8.1.2 Safety
  - 8.1.3 Liveness
  - 8.1.4 Implementing The Bounded Channel
- 8.2 The Bounded Buffer
  - 8.2.1 Modular Arithmetic
  - 8.2.2 The Algorithm
- 8.3 The Bounded Buffer Implements the Bounded Channel
  - 8.3.1 The Refinement Mapping
  - 8.3.2 Showing Implementation
  - 8.3.3 Liveness
- 8.4 A Finer-Grained Bounded Buffer
- 8.5 Further Refinement
- 8.6 What is a Process?

←

→

C

I

S

## The *Specification* Track

### 9 An Input/Output Specification

- 9.1 The Example
- 9.2 Sorting
- 9.3 Votes
- 9.4 The Borda Ranking
- 9.5 The Condorcet Ranking
- 9.6 Transitive Closure
  - 9.6.1 A Mathematical Definition
  - 9.6.2 A Definition TLC Can Execute Faster
  - 9.6.3 Warshall's Algorithm
- 9.7 The Condorcet Ranking Revisited

## The TLA<sup>+</sup> Proof Track

### 10 About Proofs and Proving

- 10.1 About Proofs

## 11 Correctness of Euclid's Algorithm

11.1 Proving Safety

11.2 Proving Properties of the GCD

## 12 The Proof Language

12.1 What a Theorem Asserts

12.2 The Hierarchical Structure of a Proof

12.2.1 Writing Structured Proofs

12.2.2 Reading Structured Proofs

12.3 The State of a Proof

12.3.1 Steps That Can Have a Proof

12.3.2 Steps That Cannot Have a Proof

12.4 Proof Obligations

12.5 Further Details

12.5.1 Additional Language Features

12.5.2 Importing

12.5.3 Recursively Defined Functions and Operators

12.5.4 The Fine Print

## 13 The Bounded Buffer Proof

# Math

## 13 Arithmetic and Logic

13.1 Arithmetic

13.2 Mathematical Logic

13.3 Propositional Logic

13.3.1  $\wedge$  and  $\vee$

13.3.2 Other Propositional Operators

13.4 Predicate Logic

13.5 The CHOOSE Operator

## 14 Sets

14.1 An Introduction to Sets

14.2 Simple Set Operators

14.3 Set Constructors

14.4 SUBSET and UNION

14.5 Collections too Big to Be Sets

14.6 Bags

?

←

→

C

I

S

## 15 Functions

- 15.1 Functions and Their Domains
- 15.2 Writing Functions
- 15.3 Sets of Functions
- 15.4 The EXCEPT Construct
- 15.5 Tuples
- 15.6 Records
- 15.7 Strings

?

←

## 16 Miscellaneous Constructs

- 16.1 Conditional Constructs
  - 16.1.1 IF / THEN / ELSE
  - 16.1.2 CASE
- 16.2 Definitions
  - 16.2.1 Simple Operator Definitions
  - 16.2.2 Function Definitions
  - 16.2.3 Recursive Operator Definitions
  - 16.2.4 Recursive Or Inductive?
- 16.3 The LET / IN Construct
- 16.4 The LAMBDA Construct

C

I

S

## 17 Temporal Logic

- 17.1 Understanding Temporal Formulas
- 17.2 Proof Rules and Proofs
- 17.3 Rules for Proving Safety
- 17.4 Leads To
  - 17.4.1 The Leads-To Induction Rule
  - 17.4.2 The  $\Box \leadsto$  Rule
  - 17.4.3 Proving  $\leadsto$  Formulas by Contradiction
- 17.5 Fairness
  - 17.5.1 The ENABLED Operator
  - 17.5.2 Weak Fairness
  - 17.5.3 Strong Fairness
  - 17.5.4 Proving  $\leadsto$  Properties with Fairness
  - 17.5.5 Proving Fairness

## Topics

### 18 Variable Hiding and Auxiliary Variables

### 19 Reduction

## 20 Debugging With TLC

20.1 Print Statements

20.2 Having TLC Set and Read Values

20.3 Using LET

20.4 The Perils of Lazy Evaluation

?

←

→

C

I

S