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Cliff B. Jones
Zhiming Liu
Jim Woodcock (Eds.)

Formal Methods and Hybrid Real-Time Systems

Essays in Honour of Dines Bjørner and Zhou Chaochen on the Occasion of Their 70th Birthdays

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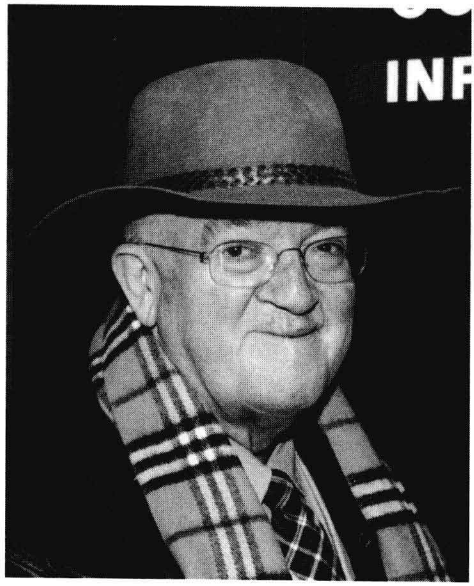

Dines Bjørner

Zhou Chaochen

Foreword

Two outstanding computer scientists will soon reach their 70th birthdays: Dines Bjørner was born on October 4, 1937 in Denmark and Zhou Chaochen was born on November 1, in the same year in China. To celebrate their birthdays, we present three LNCS volumes in their honour.

- *Formal Methods and Hybrid Real-Time Systems. Essays in Honour of Dines Bjørner and Zhou Chaochen on the Occasion of Their 70th Birthdays.* Papers presented at a Symposium held in Macao, China, September 24–25, 2007. LNCS volume **4700**. Springer 2007.
- *Domain Modelling and the Duration Calculus.* International Training School, Shanghai, China, September 10–21, 2007. Advanced Lectures. LNCS volume 4710. Springer 2007.
- *Theoretical Aspects of Computing* - ICTAC 2007. 4th International Colloquium, Macao, China, September 26–28, 2007, Proceedings. LNCS volume 4711. Springer 2007.

DINES BJØRNER is known for his many contributions to the theory and practice of formal methods for software engineering. He is particularly associated with two formal methods, although his influence is far wider. He worked with Cliff Jones and others on the *Vienna Development Method (VDM)*, initially at IBM in Vienna. Later, he was involved in producing the *Rigorous Approach to Industrial Software Engineering (RAISE)* formal method with tool support. His three-volume *magnum opus* on software engineering covers *Abstraction and Modelling*, *Specification of Systems and Languages*, and *Domains, Requirements, and Software Design*. He was a professor at the Technical University of Denmark (DTU) in Lyngby, near Copenhagen. He was the founding director of the United Nations University International Institute for Software Technology (UNU-IIST) in Macao during the 1990s. He was a co-founder of VDM-Europe, which transformed to become Formal Methods Europe, an organisation that promotes the use of formal methods. Its 18 monthly symposia have become the leading academic events in formal methods. Dines Bjørner is a Knight of the Order of the Dannebrog and was awarded the John von Neumann Medal in Budapest in 1994. He received a Doctorate (*honoris causa*) from the Masaryk University in Brno in 2004. He is a Fellow of both the IEEE and the ACM.

ZHOU CHAOCHEN is known for his seminal contributions to the theory and practice of timed and hybrid systems. His distinguished academic career started as an undergraduate in mathematics and mechanics at Peking University (1954–58) and as a postgraduate at the Institute for Computing Technology in the Chinese Academy of Sciences (1963–67). He continued his career at Peking University and the Chinese Academy, until he made an extended visit to Oxford University

Computing Laboratory (1989–92) at the invitation of Sir Tony Hoare FRS. Here he was the prime instigator of *Duration Calculus*, an interval logic for real-time systems, developed as part of a European ESPRIT project on Provably Correct Systems. He made further extended visits during the periods 1990–92 and 1995–96, as a visiting professor at the Technical University of Denmark, Lyngby, at the invitation of Dines Bjørner. He was a Principal Research Fellow at UNU-IIST during the period 1992–97, before becoming its director, an appointment he held from 1997 to 2002. He is a member of the Chinese Academy of Sciences and the Third World Academy of Sciences.

We thank both Dines Bjørner and Zhou Chaochen for their years of generous, wise advice, to us and to their many other colleagues, students, and friends. They have both been unfailingly inspiring, enthusiastic, and encouraging.

July 2007 J.C.P.W.

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Preface

This volume contains the papers presented at the *Festschrift Symposium* held September 24–25, 2007 in Macao on the occasion of the 70th birthdays of Dines Bjørner and Zhou Chaochen. It consists of 25 papers written by 59 authors. Online conference management was provided by EasyChair.

It is now difficult to remember exactly when it came to us that we should organise a celebration for the 70th birthdays of Dines Bjørner and Zhou Chaochen, which happily coincide this year. But I do know that the idea was a popular one. Zhiming Liu suggested that we should organise the symposium as part of the International Colloquium on Theoretical Aspects of Computing, which seemed perfect given that this series was founded by UNU/IIST. The event quickly took shape as He Jifeng offered to host a Training School in Shanghai with the assistance of Chris George, Geguang Pu, and Yong Zhou, and Cliff Jones agreed to help with the academic organisation of the symposium and the colloquium. Everything then just fell into place, thanks to the excellent help provided by the local organisers in Macao and Shanghai.

The subjects for the lectures for the school were obvious to us all: two topics pioneered by Dines Bjørner and Zhou Chaochen, both currently very active research areas. For the *Festschrift Symposium*, authors were invited to write on an original topic of their choosing. And for the colloquium, a general call-for-papers resulted in a satisfying collection of rigorously reviewed papers in theoretical computer science, including automata theory, case studies, concurrency, real-time systems, semantics and logics, and specification and verification.

So we have ended up with three volumes, one each for the school, symposium, and colloquium, which collectively amount to some 1,300 pages. And still there was not enough room for the many additional distinguished names we would have liked to invite.

To Dines and Chaochen from all of us:

We hope that you enjoy reading these books.

Happy birthday to both of you!

June 2007 J.C.P.W.

Organization

Programme Chairs

Cliff Jones
Zhiming Liu
Jim Woodcock

Local Organization

Kitty Chan
Wendy Hoi
Chris George
Violet Pun

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Models and Software Model Checking of a Distributed File Replication System

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Abstract. With the Distributed File System Replication component, DFS-R, as the central theme, we present selected protocol problems and validation methods encountered during design and development. DFS-R is currently deployed in various contexts; in Windows Server 2003-R2, Windows Live Messenger (Sharing Folders), and Windows Vista (Meeting spaces). The journey from an initial design sketch to a shipped product required mainly the dedicated effort of several testers, developers, program managers, and several others; but in some places cute problems related to distributed consensus and software model-checking emerged. This paper presents a few of these, including a distributed garbage collection problem, distributed consensus problems for reconciling tree-like data structures, using model-based test case generation, and the use of software model checking in design and development process.

1 Introduction

Designing and building distributed systems is challenging, especially if they need to scale, perform, satisfy customer functionality requirements, and, oh well, work. An example of a particularly challenging distributed system is multi-master, optimistic, file replication. One of the distinguished factors making distributed file replication hard is that file replication comes with a very substantial data component: the protocols need to be sufficiently aware of file system semantics, such as detecting and resolving name conflicting file creates and concurrent updates. Such races are just the tip of the iceberg. In comparison, cache coherence protocols that are known to be challenging to design, have a trivial data component, but to be fair have stronger consistency requirements.

Subtle protocol bugs can go (and have indeed gone) undetected for years due to the large number of interactions that are possible. With a sufficient number of deployments they *will* be encountered in the field, have costly consequences, and be extremely challenging to analyze. Our experience in developing DFS-R from the bottom up, is used to demonstrate several complementary uses of model-based techniques for system design and exploration. This paper provides an experience report on these selected methods. Note that the material presented here reflect only a very partial view of the design and test of DFS-R.

DFS-R was developed to address correctness, scale, and management challenges encountered with a predecessor file replication product. Thus, the original

C.B. Jones, Z. Liu, J. Woodcock (Eds.): Bjørner/Zhou Festschrift, LNCS 4700, pp. 1–23, 2007.

impression was that we had the luxury of tackling a relatively well defined problem; to build a replication system specifically handling features of the file system NTFS, for replicating files between globally dispersed branch offices of corporations. Later on, it would turn out that DFS-R could be embedded within other scenarios, such as, in an instant messenger product. However, we consciously avoided over-loading with features from the onset. It means that DFS-R, for instance does not replicate files synchronously, only asynchronously (as it is meant for wide area networks); does not replicate general directed acyclic graphs, only tree-like structure; and does not maintain fine-grained tracking of operations, only state. While several such problems are interesting in other contexts, they did not fall into the scope of our original goals.

The organization of this paper follows the top-down design flow of DFS-R. The DFS-R system was originally conceived as a strictly state-based file replication protocol. Section 2 elaborates on the differences between state-based and operations-based replication systems. We developed a high-level state machine specification of DFS-R by using a transition system presented as a collection of guarded commands. The guarded commands were subsequently implemented as an applicative program in OCaml. This paved the way for performing efficient state space exploration on top of the design. Section 3 elaborates on the protocol, and Section 4 summarizes prototyping experiences. As the development took place, several assumptions made in the abstract design turned out to be unrealistic, and we redid the high-level design using the AsmL tools that were built at Microsoft for software modeling and test case generation. Section 5 elaborates on the experiences from using AsmL. A number of well-separated distributed protocol problems emerged during the development. Section 6 describes the distributed tree reconciliation problem, and how we used a model checker, Zing, to expose bugs in both protocol proposals and legacy implementations. Section 7 describes the distributed tombstone garbage collection problem and a solution to it. While one cannot expect to get anywhere without a high-level understanding of the protocols involved in DFS-R, it is equally unrealistic to expect developing a production quality system without addressing systems problems. We were thus faced with a potentially large gap between simplified protocol substrates and the production code. Encouraged by the ability of the model-based state space exploration to expose subtle interaction bugs we repeated the state space exploration experiment on top of the production core. The resulting backtracking search tool may best be characterized as a hybrid software model checking, run-time verification tool. It operates directly at the source code level. It uses techniques, such as partial order reduction to prune search and custom allocation routines to enable backtracking search. Section 8 describes the infrastructure we developed and the experiments covering $\frac{1}{2}$ trillion scenarios.

2 File Replication

The style of replication systems under which DFS-R falls into is surveyed extensively in [1]. We here summarize a few of the main concepts relevant for

DFS-R. The problem that DFS-R solves is to maintain mirror copies of selected directories across large networks of servers. The directories that are selected for replication are called *replicated folders.* Files and directories within these directories may be created, modified, deleted, moved, or renamed at any of the mirror sites. It is the job of DFS-R to distribute changes, detect and reconcile conflicts automatically when they arise. Distributed replication systems can be categorized according to what problems they solve and how they solve them. Figure 1 summarizes some of the main design choices one has when designing a replication system.

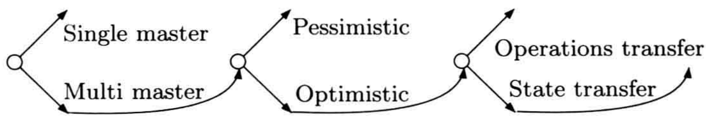

Fig. 1. Replication system ontologies

Multi Master Replication. DFS-R is a multi-master replication system. Any machine may participate in changing resources, and their updates will have to be reconciled with updates from any other machine. A (selective) single-master system only replicates changes from a set of selected machines. All other machines are expected to maintain a mirror copy of the masters. This would mean that file system changes on non-masters would have to be reverted. If there is a designated master, one can even choose to maintain truth centrally. The challenge there is managing fail-over and network disconnects.

Optimistic Replication. To support wide area networks (spanning the globe) DFS-R supports optimistic updates to files. This means that any machine may submit updates to resources without checking first whether the update is in conflict with other updates. Pessimistic replication schemes avoid concurrent update conflicts by serializing read and write operations using locking schemes.

State and Operation Transfer. A file system state is the result of the file operations (create, update, delete, move) that are performed on it. This suggests two approaches to realize file replication: intercept and replay the file operations, called operation transfer, or capture the file system state and replicate it as it is, called state transfer. DFS-R implements a state transfer protocol. There are several hard challenges with operations-transfer based systems. One is merging operations into a consistent serialization. Another, is space, as operations are not necessarily amenable to garbage collection.

Perspective. There is no single choice of design parameters that handles all customer scenarios. In some configurations, corporations wish to designate machines as read-only, and can manage the additional constraints this leaves on