# Developing Embedded/Real-Time and Cyber-Physical Systems: Functional Reactive Programming, RTL-based Formal Verification, Response Time Analysis, and Power-Aware Scheduling

Albert M. K. Cheng
Real-Time Systems Laboratory
Department of Computer Science
University of Houston
Houston, TX 77204, USA
Email: cheng@cs.uh.edu

## 1. Audience and Duration

This tutorial is for anyone interested in the state-of-the-art technology for developing embedded, real-time, and cyber-physical systems. The focus is on functional reactive programming, RTL (real-time logic)-based formal verification, response time analysis, and power-aware scheduling. Knowledge of basic operating systems and architecture concepts are assumed. The duration is two hours.

## 2. Tutorial Description

The use of sophisticated digital systems to control complex physical components in real-time has grown at a rapid pace. These applications range from traditional stand-alone systems to highly-networked cyber-physical systems (CPS), spanning a diverse array of software architectures and control models. Examples include automobile adaptive braking, industrial robotic assembly, medical pacemakers, autonomous (ground, air, and sea) vehicular travel, remote surgery, physical manipulation of nano-structures, and space exploration. Since all these applications interact directly with the physical world and often have humans in the loop, we must ensure their physical safety.

Obviously, the correctness of these embedded systems and CPSs depends not only on the effects or results they produce, but also on the time at which these results are produced. For example, when the driver of a car applies the brake, the anti-lock braking controller analyzes the environment in which the controller is embedded (car speed, road surface, direction of travel) and activates the brake with the appropriate frequency within fractions of a second. Both the result (brake activation) and the time at which the result is produced are important in ensuring the safety of the car, its driver and passengers. In a CPS consisting of a multitude of

vehicles and communication components with the goal to avoid collisions and reduce traffic congestions, formal safety verification and response time analysis are essential to the certification and use of such systems.

In battery-operated real-time systems such as sensors in a CPS, conserving energy is of critical importance. Power-aware scheduling plays a key role in ensuring uninterrupted operation of these systems between battery recharges or energy-harvesting.

This tutorial covers the following topics:

(1) Introduction to embedded/real-time and cyber-physical systems;
(2) Functional reactive programming
(3) Formal specification methodology and requirements analysis;
(4) Analysis tools for performance evaluation;
(5) System decomposition, multiprocessor scheduling, and resource partitioning;
(6) Development tools;
(7) Real-time operating systems;
(8) Formal analysis, verification, and validation techniques based on Real-Time Logic (RTL);
(9) Power-aware scheduling;
(10) Response time analysis;
(11) Optimization and synthesis; and
(12) Case studies of actual systems (such as the timing analysis of the X-38 Space Station Crew Return Vehicle Avionics consisting of a fault-tolerant distributed system of a network of processors).

## 3. Instructor's Biography

Albert M. K. Cheng is Professor and former interim Associate Chair of the Computer Science Department at the University of Houston (UH). His research interests center on the design, specification, modeling, scheduling, and formal verification of real-time, embedded, and cyber-physical systems, green/power/thermal-aware computing, software engineering, knowledge-based systems, and networking. He is the founding Director of the UH Real-Time Systems Laboratory. He received the B.A. with Highest Honors in Computer Science, graduating Phi Beta Kappa at age 19, the M.S. in Computer Science with a minor in Electrical Engineering at age 21, and the Ph.D. in Computer Science at age 25, all from The University of Texas at Austin, where he held a GTE Foundation Doctoral Fellowship. He has served as a technical consultant for many organizations, including IBM and Shell, and was also a visiting professor in the Departments of Computer Science at Rice University and at the City University of Hong Kong. He is a co-founder of ZapThru.com, where he is currently the Chief Technology Advisor.

Dr. Cheng is the author/co-author of over 170 refereed publications in leading journals (including IEEE Transactions on Computers, IEEE Transactions on Software Engineering, and IEEE Transactions on Knowledge and Data Engineering) and top-tier conferences (including RTSS, RTAS, RTCSA, ICESS, ICPADS, ISLPED, LCN, ICMCS, COMPSAC, AINA, PADL, IPPS, IPDPS, and ICPP), and has received numerous awards, including the U.S. National Science Foundation Research Initiation Award and the Texas Advanced Research Program Grant. He has been invited to present seminars, tutorials, panel positions, and keynotes at over 80 conferences, universities, and organizations. He is and has been on the technical program committees (including several program chair positions) of over 200 conferences, symposia, workshops, and editorial boards (including the IEEE Transactions on Software Engineering 1998-2003 and the IEEE Transactions on Computers 2011-present). Dr. Cheng is the author of the popular senior/graduate-level textbook entitled Real-Time Systems: Scheduling, Analysis, and Verification (Wiley), 2nd printing with updates, 2005. He is a Senior Member of the IEEE and has been nominated to become an IEEE Fellow in 2012; an Honorary Member of the Institute for Systems and Technologies of Information, Control and Communication (INSTICC); and a Fellow of the Institute of Physics (IOP).

## Acknowledgment

The work described is supported in part by the U.S. National Science Foundation under Awards No. 0720856 and No. 1219082.

## Selected References

Albert M. K. Cheng, Real-Time Systems: Scheduling, Analysis, and Verification (John Wiley & Sons), 2002. and 2005.

S. Andrei and A. M. K. Cheng, "Efficient Verification and Optimization of Real-Time Logic Specified Systems," IEEE Transactions on Computers, vol. 58, no. 12, December 2009.

Y. W. Ahn, C. Belwal, A. M. K. Cheng, and J. Baek, "Improving QoS for Wireless ECG Data Transmission with Enhanced Admission Control in EDCA-Based WLANs," IEEE Globecom, Houston, Texas, December 5-9, 2011.

Chaitanya Belwal and Albert M. K. Cheng, ``Lazy vs Eager Conflict Detection in Software Transactional Memory: A Real-Time Schedulability Perspective," IEEE Embedded Systems Letters, March 2011.

Chaitanya Belwal and Albert M. K. Cheng, "Determining Actual Response Time in P-FRP," 13th Intl. Symp. Practical Aspects of Declarative Languages (PADL), Austin, Texas, USA, Jan. 2011.

Hua Chen, Albert M. K. Cheng, and Ying Kuo, "Assigning Real-Time Tasks to Heterogeneous Processors by Applying Ant Colony Optimization," J. Parallel and Distributed Comp., January 2011.

Jian (Denny) Lin and Albert M. K. Cheng, "Energy Reduction for Scheduling a Set of Multiple Feasible Interval Jobs," Special Issue (SI) on Selected Top Papers of RTCSA 2009, Journal of Systems Architecture: Embedded Software Design, Elsevier, Nov. 2010.

Jim Ras and Albert M. K. Cheng, "Response Time Analysis of the Abort-and-Restart Model under Symmetric Multiprocessing," ICESS, Bradford, UK, June 2010. **Best Paper Award Nominee.**

Stefan Andrei and Albert M. K. Cheng, "Decomposition-based Verification of Linear Real-Time Systems Specifications," 2nd Workshop on Compositional Theory and Technology for Real-Time Embedded Systems (CRTS), Washington, D.C., Dec. 2009.

Jim Ras and Albert M. K. Cheng, "Response Time Analysis for the Abort-and-Restart Event Handlers of the Priority-Based Functional Reactive Programming (P-FRP) Paradigm," RTCSA, Beijing, China, Aug. 2009. **Best Paper Award Nominee.**

Jian (Denny) Lin and Albert M. K. Cheng, "Power-aware scheduling for Multiple Feasible Interval Jobs," RTCSA, Beijing, China, Aug. 2009. **Best Paper Award Nominee.**

Jim Ras and Albert M. K. Cheng, "An Evaluation of the Dynamic and Static Multiprocessor Priority Ceiling Protocol and the Multiprocessor Stack Resource Policy in an SMP System," RTAS, San Francisco, CA, April 2009.

Jim Ras and Albert M. K. Cheng, "Real-Time Synchronization on Distributed Architecture with Ada 2005," ACM Intl. Conference on the Ada Programming Language, Portland, Oregon, Oct. 2008.

A. M. K. Cheng, "Cyber-Physical Medical and Medication Systems," First CPS Workshop, Beijing, China, June 2008.

S. Andrei and A. M. K. Cheng, "Verifying Linear Real-Time Logic Specifications," RTSS, Tucson, AZ, Dec. 2007.

Albert M. K. Cheng and Jim Ras, "Event-Based Semantics in the Implementation Language for Embedded and Critical Systems," Event-Based Semantics Workshop, April 2007.

S. Andrei and A. M. K. Cheng, "Faster Verification of RTL-Specified Systems via Decomposition and Constraint Extension," RTSS, Rio de Janeiro, Brazil, December 2006.

Yu Li and Albert M. K. Cheng, "Static Approximation Algorithms for Regularity-based Resource Partitioning," to appear in 33rd Real-Time Systems Symposium (RTSS), San Juan, Puerto Rico, USA, December 4-7, 2012.