Guest Editors' Introduction

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We, the co-guest editors, are extremely honored to have the opportunity to write this introduction on behalf of a true pioneer, B. Ramakrishna (Bob) Rau. Bob was born in 1951 and received his Bachelor's degree from IIT Madras and his Master's degree from Stanford University. After receiving his Master's degree, he joined Palyn, a company cofounded by Mike Flynn, aimed at IBM 370 compatible mainframe design. Through his work at Palyn, he became deeply passionate about computer architecture. As a result, he went back to Stanford and finished his PhD degree in 1977. After receiving his PhD, Bob launched his research career as an assistant professor at the University of Illinois, Urbana-Champaign, where he developed the early concept of his work in VLIW (Very Long Instruction Word) computing. In 1980, Bob, along with another assistant professor, Mike Schlansker, left academia and joined TRW's Array Processors Division. This can be viewed as either one of the biggest losses of the University of Illinois or one of the greatest gifts from the University of Illinois to the computer industry.

Bob is widely recognized for his technical leadership and pioneering contributions to the field of VLIW computing. He and fellow VLIW pioneer Josh Fisher led the development of this field as senior fellows at HP Laboratories. In this context and over the past two decades, Bob's individual and collaborative contributions have helped define VLIW computing through seminal research, publications, products, and patents. VLIW architectures are now the de-facto standard in architectures for virtually all high-performance, low-power embedded processors, including those for DSP. Equally significantly, this work is the foundation of Intel's Explicitly Parallel Instruction Computing (EPIC), which has resulted in the currently available Itanium family of processors. Bob was the intellectual force behind many key concepts and innovations that enabled modern VLIW and EPIC architectures and their compilers. He is an inventor or co-inventor of ideas such as architectural support for predicated execution and hardware support for compile-time speculation of operations above branches. He is also a pioneering innovator in the area of VLIW/EPIC compilation, having introduced new concepts of fundamental importance such as modulo scheduling, the pervasive application of predicated execution to modulo scheduled loops, software-based data cache management, and region-based compilation. He held 15 patents and published 25 widely cited and used publications on these topics.

Bob's vision and influence have their early roots in Cydrome Inc., a company that he cofounded where he led the development of the Cydra 5 VLIW mini-supercomputer —viewed by many as one of the most architecturally innovative computers. Some of the key ideas from this era were published in "The Cydra 5 Departmental Supercomputer: Design Philosophies, Decisions and Trade-Offs," B. R. Rau, D.W.L. Yen, W. Yen, and R.A. Towle, *Computer*, vol. 22, pp. 12-35, 1989. Cydrome's compiler technology was commercially used by a number of companies, including Hewlett-Packard, Toshiba, and SGI. After Cydrome, Bob joined Hewlett Packard and attracted Josh Fisher to HP, where they led HP Laboratories' highly recognized research program in instruction-level parallel (ILP) computing. Bob focused on an ILP research program with the view of evolving the Cydra 5 VLIW architecture to excel in the context of general-purpose applications. This work is the crucial ingredient in the HP-Intel alliance that yielded the EPIC-based Intel Itanium family of architectures. Much of this research and related contributions are embodied in the *Trimaran* (www.trimaran.org) infrastructure. Bob was the catalyst in establishing the collaboration between the CAR group that he was leading at HP Labs and our two research groups—the three arms of Trimaran. Released to the public in 1997, this freely available infrastructure has been and continues to be used world-wide in research and in education and is a symbol of Bob's vision and legacy. Over the years, Bob also played a significant role in enabling, stimulating, and supporting research at major research universities. For example, he coauthored the very influential article with Josh Fisher entitled "Instruction-Level Parallel Processing: History, Overview, snd Perspective," B.R. Rau and J.A. Fisher, *The Journal of Supercomputing*, vol. 7, pp. 9-50, 1993. A popular version of this article also appeared in the influential journal *Science* in September of 1991.

Moving past his EPIC contributions, Bob directed the Program-In-Chip-Out (PICO) project with the goal of creating the capability for automatically architecting custom, application-specific computing systems aimed at the burgeoning embedded systems domain. His legacy has continued in the form of a business, Synfora, led and managed by members of his old team. In this context, he is a co-inventor of 11 of the 27 patent applications. Rooted firmly in his pioneering contributions to instruction-level parallelism and VLIW, PICO is able to take an application written in C and automatically "synthesize" a high-quality

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EPIC processor as well as a nonprogrammable accelerator (NPA) for it. Through customization, the NPA provides far greater performance per square unit of target silicon and, thus, yields a near-optimal design from a cost-performance viewpoint.

In 2001, he was elected a fellow of the IEEE and, immediately prior to his passing away in 2003, he was elected a fellow of the ACM. In recognition of his leadership and sustained contributions over his career, Bob was recognized and honored in many other ways. In 2002, he received the IEEE Computer Society's Eckert-Mauchly Award—the most prestigious award for computer architecture. Since 1996, he had been an HP Fellow and, upon creation of the title, a Senior Fellow, both of which were, at the time he held them, the highest technical positions at HP.

An unwavering theme underlying Bob's philosophical and technological vision that guided his research agenda is rooted in a need to sustain Moore's law and its profound cost-performance consequences driving the unparalleled growth of the computing industry. In his earlier quest, culminating in the advancement of VLIW and EPIC, this pursuit took the rather bold step of recognizing—in retrospect, correctly—that moving functionality to the compiler (software) from the architecture and microarchitecture (hardware) was a key to sustaining this promised growth within the context of microprocessor design. As testimony to this impact, VLIW and EPIC, in large measure, represent the conventional wisdom in microprocessor design today. Perhaps what is rather unique about his style and successes is the pursuit of ideas that have shaped the heart of computing as it stands today—computer architecture and the optimizing compilers for leveraging them—at the highest levels. This achievement of "impact in the large" is especially rare in a world increasingly filled with good, albeit evolutionary and incremental, ideas. His vision and, perhaps equally importantly, an ability to articulate it with impeccable clarity and pedagogical perspective within the context of a rapidly emerging technology and commercial mosaic, will be his lasting legacy to our field.

Impressive as Bob's technical impact was, what is so special about Bob is that he has left an incredibly rich legacy to our community, far beyond his research contributions. Many of us will remember Bob as an insightful speaker with a great sense of humor. In his 1992 ISCA keynote, he put Christopher Columbus on trial and questioned the likelihood of him being tenured at a modern US university. Through his talk, he offered great insight on evaluating the quality of academic research in computer architecture. In 1992, Bob gave a dinner speech at MICRO entitled "How to Sink Your Company without Trying," where he gave an excellent account of his journey in pursuing his vision in the midst of major industry changes and setbacks. Many of us will remember Bob as a great mentor, whose enthusiasm for knowledge and interpersonal relationships was truly contagious. Our collaborations with Bob have influenced us in the manner in which we think and the way in which we work with people. We constantly find ourselves asking the question "What would Bob do in this situation?" And we, for sure, were fortunate enough to be able to pick the phone and ask him that question.

Most significantly, Bob will be remembered as a true gentleman who was respected immensely, both by his collaborators and, unusually, by his competitors. It is only natural for long-time collaborators, such as the two of us who are writing this preface, to respect Bob for his enormous intellectual strength, true dedication to humanity, and generous contributions. What is truly impressive is that his competitors openly and repeatedly expressed their respect for him. Bob's Eckert-Mauchly Award acceptance speech shed some light on the reasons underlying this impressive fact. There, he taught us the "Rau Principle," which we paraphrase as "never presume that a technology failed until the proponents who dedicate their lives to developing the technology give up." We believe that it is this healthy respect for his competitors that helped in winning him their respect in return.

As a way of helping perpetuate his historic contributions and his lasting legacy as a researcher and as a truly valuable human being through the annals of this seminal journal, we chose to select the best papers for review from two conferences that we felt embodied Bob's vision and aspirations and which he helped grow into international symposia of note: the IEEE/ACM International Symposium on Microarchitecture (MICRO) and the Conference on Compilers, Architecture, and Synthesis for Embedded Systems (CASES). The selected papers were submitted to the usual rigorous review process and the six papers deemed most worthy appear in this special section dedicated to Bob's memory. We feel that these papers are fitting "standard bearers" of Bob's ideas in spirit, philosophy, and in importance. It has been a privilege to be able to contribute to helping shape this memorial issue, as much as it has been a rare privilege indeed to have collaborated with Bob during his truly significant life and to have shared in some of his seminal contributions. Bob accomplished, by his early fifties, what most people who are viewed as leaders in the field of computing would have been flattered to have been associated with in a much longer lifetime of contributions!

Wen-mei W. Hwu
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Guest Editors

Wen-mei W. Hwu (S'78, M'88, F'98) received the PhD degree in computer science from the University of California, Berkeley. He is the Sanders-AMD Endowed Chair Professor at the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign. From 1997 to 1999, he served as the chairman of the Computer Engineering Program at the University of Illinois. His research interest is in the area of architecture, implementation, and software for high-performance computer systems. In particular, his research activities are focused around novel computer architectures and the compiler techniques required by these architectures. He is well-known for his contributions to the development of compiler technology for predicated execution and speculative execution in EPIC architectures. His recent work has mostly been in the area of deep program analysis and its applications to compiler transformations and advanced memory architectures. He is the director of the IMPACT lab (www.crhc.uiuc.edu/Impact), which has delivered new compiler and computer architecture technologies to the computer industry since 1987. For his contributions to the areas of compiler optimization and computer architecture, he received the 1993 Eta Kappa Nu Outstanding Young Electrical Engineer Award, the 1994 Xerox Award for Faculty Research, the 1994 University Scholar Award of the University of Illinois, the 1997 Eta Kappa Nu Holmes MacDonald Outstanding Teaching Award, the 1998 ACM SigArch Maurice Wilkes Award, the 1999 ACM Grace Murray Hopper Award, and the 2001 Tau Beta Pi Daniel C. Drucker Eminent Faculty Award. He is a fellow of the IEEE and the ACM. He serves on the Executive Committees of the MARCO/DARPA C2S2 (www.c2s2.org) and GSRC (wwww.gigascale.org) Focus Research Centers. He also serves on the GELATO Strategy Council (www.gelato.org).

Krishna V. Palem (S'80, M'86, F'04) has held a professorship in electrical and computer engineering and in computer science at the College of Computing, a senior research leadership in the College of Engineering, and has been the founding director of the Center for Research in Embedded Systems and Technology (CREST) (www.crest.gatech.edu) at the Georgia Institute of Technology since 1999. He has worked with and led efforts internationally in the area of embedded systems, having founded one of the earliest laboratories for research in academia dedicated to this field in 1994—the Real-time Compilation Technologies and Instruction Level Parallelism (ReaCT-ILP) laboratory at the Courant Institute of Mathematical Sciences, New York University, where he was a tenured faculty member. The work pursued there led to the widely used TRIMARAN system (www.trimaran.org), codeveloped with the CAR group of HP-Labs and the IMPACT project of the University of Illinois. From 1986 to 1994, he was a member of the IBM T.J. Watson Research Center. During this period, he met Bob Rau while he was serving as an advanced technology consultant to IBM's Santa Teresa Laboratory in the area of compiler optimizations. His efforts at the ReaCT-ILP laboratory were recognized with awards for excellence from Hewlett-Packard, IBM, and Panasonic. Another highlight of these research accomplishments is the award-winning dissertation of his PhD advisee, Suren Talla. As part of this research, Dr. Palem laid the foundations of architecture assembly which the prestigious Analysts' Choice Awards recognized by nominating it as one of the outstanding technologies of 2002. With Guang Gao, he started the Compilers, Architectures, and Synthesis for Embedded Systems (CASES) workshop series in 1998. Since then, this workshop has blossomed into a major international conference sponsored by ACM SIGs and the IEEETC, serving the community as a point of focus for quality research. He has chaired bodies whose advice has led to funding initiatives in embedded and hybrid systems in the US and overseas. He was a Schonbrunn visiting professor at the Hebrew University of Jerusalem, Israel, where he was recognized for excellence in teaching, and has held visiting positions at the National University of Singapore and the École Normale Supérieure in Paris. He is a fellow of the IEEE.