

# Context-Aware Pervasive Systems

Architectures for a New Breed of Applications



SENG LOKE



Auerbach Publications  
Taylor & Francis Group

TP301  
L836

# Context-Aware Pervasive Systems

Architectures for a New Breed of Applications



**SENG LOKE**



E2007002264



**Auerbach Publications**

Taylor & Francis Group  
Boca Raton New York

---

Auerbach Publications is an imprint of the  
Taylor & Francis Group, an informa business

Auerbach Publications  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2007 by Taylor & Francis Group, LLC  
Auerbach is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works  
Printed in the United States of America on acid-free paper  
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-7255-0 (Hardcover)  
International Standard Book Number-13: 978-0-8493-7255-1 (Hardcover)

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

No part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC) 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

---

**Library of Congress Cataloging-in-Publication Data**

---

Loke, Seng.  
Context-aware pervasive systems : architectures for a new breed of applications  
/ Seng Loke.  
p. cm.  
Includes bibliographical references and index.  
ISBN 0-8493-7255-0 (alk. paper)  
1. Ubiquitous computing. 2. Mobile computing. 3. Software architecture. I.  
Title.

QA76.5915.L65 2006  
005.1'2--dc22

2006049923

---

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>

and the Auerbach Web site at  
<http://www.auerbach-publications.com>

---

# DEDICATION

To my Creator who knows all about aware systems, living and nonliving.

In memory of my dad (1936–1998) who is now much more aware  
of important things and the Lord Jesus Christ.

---

# PREFACE

Context-aware mobile computing has been a topic for research since one of the earliest Ph.D. dissertations appeared on the topic in 1994. Recently, context-aware computing has enjoyed remarkable attention from researchers in diverse areas such as distributed computing and human-computer interaction. Such aware systems have become one of the most exciting concepts in early 21st-century computing, fueled by recent developments in pervasive computing (i.e., mobile and ubiquitous computing) including new computers worn by users, embedded devices, smart appliances, and sensors surrounding users and varieties of wireless networking technology. Software and hardware systems that are ubiquitous and aware of users, and their physical and virtual context (e.g., environment and circumstances), and can respond intelligently to what is perceived is an exciting, if not increasingly vital, addition to daily life and work. Whereas the idea of context has been studied in logic and the meaning of natural language sentences, the notion of context is being revisited in mobile and ubiquitous computing work. The experience economy has taught us that experience matters, and context awareness is a key idea for providing new experiences with devices, appliances and software systems, and automatic behaviors for convenience and innovative applications.

This book is a gentle introduction to a new breed of computer applications termed *context-aware pervasive systems*, and attempts to provide architectural blueprints for building context-aware behavior into applications. The book reviews the anatomy of context-aware pervasive applications, including:

- Context-aware mobile services
- Context-aware devices, appliances, and smart things
- The integration of context-aware computing with software agents and the Web

- The use of context awareness for addressing, and communication between, people, devices, and software agents
- Context-aware controlled sensor networks
- Context-aware security frameworks
- Context awareness via mirror worlds

In this book we aim to capture general design principles and architectures for context-aware applications. These applications are certainly not exhaustive and only serve to illustrate the usefulness and potential of context awareness in mobile and ubiquitous systems, and the range and diversity of context-aware behaviors, to the extent that can be done within one book. The book also highlights the notion of *mirror worlds* (a term I believe originated in Gelernter's book) and its interesting applicability to building aware systems, and discusses declarative approaches to constructing such systems. I have often used examples from my own work to illustrate the concepts presented here, perhaps not surprisingly; where appropriate, I have noted work by others in the area. Although related work has been surveyed, there is work which I have left out, given the extent of activity in the area. I trust that readers will find the extensive set of references useful, and use this book as a platform to further explore the area.

Context-aware pervasive computing is still an area of active research, and we will indeed develop a deeper understanding of such systems, better techniques, and architectures of greater generality. Hence, one faces a dilemma about writing a book too early for an area that is still growing and in many ways changing. Nevertheless, I feel that there is a need for such a book, serving as a timely and relevant introduction to the emerging breed of context-aware systems, and presenting an initial step toward bringing together in one volume architectures and principles — as they relate to the applications covered — of such systems, providing material already in use by practitioners and enthusiasts in an exciting field.

One of the titles initially selected for this book was *Inside Aware Systems: Introducing the Software Architectures of a New Breed of Applications*. Dropping the “context” from “context-aware” is a move toward a more general concept, which perhaps this book can help develop.

Readers can become acquainted here with an increasingly important new breed of software and their implications and possibilities, even if they are not experts in the field or directly work in the area. Students and researchers new to the area can quickly obtain familiarity with key ideas and concepts of the topic, all in one place, acquiring a framework by which to understand related work and perhaps to start working in the area. Practitioners can take the designs and architectures presented and implement their own versions of the systems, adding their own features

or improvising as their applications require. Researchers from other areas can find application of their own expertise within the area of aware systems, based on the abstract architectures presented here. Nontechnical readers, skipping over the technical material, will still be able to gain an appreciation for the ideas and concepts within the area.



---

# ACKNOWLEDGMENTS

This book existed in an early form in bits and pieces, distributed in several papers, and published in a number of conference and workshop proceedings and journals over the past few years. The substance of this book is not the work of one person. I would like to thank the many graduate students and colleagues who worked with me on these topics and continue to do so. To mention a few, Evi Syukur, Thin Thin Naing, and Angel On Kei Tam worked on mobile services; Sutardi on the context-aware mobile phone prototype; Shonali Krishnaswamy, Andiwijaya Sumartono, and Su Hui Chuah on the CALMA agent-based Web service framework; and Amir Padovitz and Arkady Zaslavsky on context-aware messaging and context modeling. Suan Khai Chong and Shonali worked with me on context-aware sensors (Chapter 7 is, in fact, based on a draft paper that Khai wrote); Yong Jin Sim on a mutual awareness model for devices (mentioned in Chapter 9), and Pravin Shetty explored context-aware security with me. I also would like to thank Toan Phung, Budi Halim, and Jonathan Yu for helping with the location-based agents' prototype and contributing ideas over their summer vacation. The students helped turn what is in our imagination into real working systems on real devices, and I thank them for giving me the satisfaction of seeing my imagination crystallized. The Mobility, Agents and Pervasive Systems Group at Monash University, Caulfield, Melbourne, was a wonderful environment in which to think, pursue, and realize new ideas and concepts.

I completed this book at La Trobe University's Department of Computer Science and Computer Engineering, and I would like to acknowledge the conducive and supportive department that it is. It is both encouraging and invigorating to be in an environment excited about pervasive computing.



---

## ABOUT THE AUTHOR

**Dr. Seng Loke** is currently a senior lecturer in the Department of Computer Science and Computer Engineering at La Trobe University, Melbourne, Australia, and is also an honorary associate of the Center for Distributed Systems and Software Engineering at Monash University. He was previously a senior fellow at Monash University. He has published more than 130 papers as book chapters and in journals, conferences, and workshops. He co-leads the Pervasive Computing Group at La Trobe.

---

# CONTENTS

<b>1</b>	<b>What Is Context-Aware Behavior?</b>	<b>1</b>
1.1	Current Computing Trends: From the Virtual to the Physical	2
1.2	Context, Context Awareness, and Situations	4
1.3	When Systems Become Context Aware	7
1.4	An Overview of This Book	8
	References	10
<b>2</b>	<b>The Structure and Elements of Context-Aware Pervasive Systems</b>	<b>13</b>
2.1	Analogies	13
2.2	The Elements of a Context-Aware Pervasive System	15
2.2.1	Sensing	15
2.2.2	Thinking	20
2.2.3	Acting	24
2.3	An Abstract Architecture	24
2.4	Infrastructures, Middleware, and Toolkits	26
2.5	Issues of Security, Privacy, and Efficiency	27
2.6	Summary	27
	References	28
<b>3</b>	<b>Context-Aware Mobile Services</b>	<b>31</b>
3.1	The Rise of Mobile Services	31
3.2	Context for Mobile Device Users	33
3.3	Location-Based Services	33
3.4	Ambient Services	34
3.4.1	PointRock Example	37
3.4.2	Future E-Marketplaces	38
3.4.3	Office Building Example	42
3.4.4	A Software Architecture for Ambient Services	44
3.5	From Ambient Services to Place-Based E-Communities	49
3.5.1	Interaction between User and Community Server	50

3.5.2	Interaction between User and Multiple Communities: Impact of User Movement.....	51
3.6	Enhancing Context-Aware Mobile Services with Mobile Code and Policy: The MHS Example .....	52
3.6.1	MHS Architecture .....	53
3.6.1.1	Policy Conflict Resolution .....	54
3.6.2	Context-Based Policy Control of Media Player Service .....	55
3.6.3	Partial Control between User and System .....	60
3.6.4	MHS Summary.....	61
3.7	Enhancing Context-Aware Mobile Services with Multiagent Technology: The Example of Proximity-Based Reverse Auctions.....	61
3.7.1	Proximity-Based Reverse Auctions .....	61
3.7.2	A System for Proximity-Based Reverse Auctions .....	63
3.7.2.1	Architectural Overview .....	63
3.7.2.2	From the User's Viewpoint .....	65
3.7.2.3	Interaction Protocols.....	67
3.7.2.4	Observing Auctions via Auction Events .....	68
3.8	Summary and Further Developments.....	70
	Acknowledgment .....	71
	References.....	71
<b>4</b>	<b>Context-Aware Artifacts .....</b>	<b>75</b>
4.1	Aware Objects.....	75
4.2	Architectural Design Space for a Context-Aware Artifact .....	82
4.3	Context-Aware Mobile Phones: An Illustration.....	84
4.3.1	Overview of a Framework for Context-Aware Mobile Phone with User Preferences: The CAMP-UP System .....	84
4.3.2	CAMP-UP System Interaction .....	85
4.3.2.1	On the Space Side.....	87
4.3.2.2	On the Client Side.....	88
4.3.3	Prototype and Discussions .....	90
4.3.4	Scenarios .....	93
4.4	Summary.....	99
	References.....	100
<b>5</b>	<b>Context-Aware Mobile Software Agents for Interaction with Web Services in Mobile Environments.....</b>	<b>105</b>
5.1	Agents: Mobile and Intelligent .....	105
5.2	Scenarios .....	106
5.3	A Brief Review of Agent Platforms for Ubiquitous Computing.....	108
5.4	CALMA Architecture .....	109
5.4.1	CALMA Agent Model .....	111
5.4.2	Server Component .....	115
5.4.3	Mobile Device Component .....	116
5.5	Prototype Implementation and Evaluation.....	116
5.5.1	Illustrative Scenarios .....	117
5.5.1.1	Booking Movie Tickets .....	117

5.5.1.2	Finding an IDD Calling Card.....	117
5.5.2	Enabling Lightweight Behavior.....	120
5.5.3	Enabling Context Awareness.....	122
5.5.4	Performance Evaluation.....	122
5.6	Summary.....	124
	Acknowledgments.....	125
	References.....	125
<b>6</b>	<b>Context-Aware Addressing and Communication for People, Things, and Software Agents.....</b>	<b>127</b>
6.1	Context-Aware Communication for People.....	128
6.1.1	Application Types.....	128
6.1.2	Call Services.....	131
6.1.3	More Applications.....	132
6.1.4	Summary.....	133
6.2	Context-Aware Addressing and Commanding for Objects.....	133
6.2.1	Application Types.....	133
6.2.2	A View from Situation Semantics.....	134
6.2.3	Summary.....	137
6.3	Context-Aware Communication for Software Agents.....	138
6.3.1	Addressing Agents via Context.....	138
6.3.2	Applications.....	139
6.4	Summary and Conclusion.....	140
	References.....	141
<b>7</b>	<b>Context-Aware Sensor Networks.....</b>	<b>143</b>
7.1	Context-Aware Sensors: The Concept.....	143
7.2	A Framework for Context-Aware Sensors.....	145
7.2.1	Sensor Roles.....	145
7.2.2	Categorizing Energy Consumption.....	146
7.2.2.1	Input Alphabet.....	146
7.2.2.2	Output Alphabet.....	147
7.2.2.3	Energy States.....	148
7.2.3	Architecture.....	148
7.3	Implementation and Application Scenario.....	152
7.3.1	Experimental Investigations.....	153
7.4	Summary.....	156
	Acknowledgment.....	156
	References.....	157
<b>8</b>	<b>Context-Aware Security.....</b>	<b>159</b>
8.1	Traditional Security Issues and Models.....	161
8.2	Context-Aware Security Systems.....	162
8.2.1	Examples.....	162
8.2.2	Context-Aware Policies.....	164
8.2.2.1	Contextual Graphs.....	165
8.2.2.2	Logic.....	166
8.2.2.3	Roles.....	167

8.3	From Context-Aware Security to Context-Aware Safety .....	169
8.4	Summary.....	170
	References.....	170
<b>9</b>	<b>Context Awareness and Mirror-World Models .....</b>	<b>173</b>
9.1	Gelernter's Mirror Worlds .....	173
9.2	Nexus.....	175
9.3	Virtual Worlds, Virtual Environments.....	176
9.3.1	Aura, Focus, and Nimbus: Virtual Objects and Real-World Objects .....	177
9.4	Digital Cities.....	181
9.5	Aware Spaces: Smart Environments and Smart Spaces.....	183
9.6	Mirror Worlds: Context and Ontologies .....	185
9.7	Summary.....	186
	References.....	186
<b>10</b>	<b>Constructing Context-Aware Pervasive Systems: Declarative Approaches and Design Patterns .....</b>	<b>189</b>
10.1	Representing Situations .....	190
10.1.1	The Situation Program.....	191
10.1.2	Modularity .....	193
10.2	Five Other Ways to Represent a Meeting .....	194
10.2.1	Observations.....	197
10.3	Metaprogramming with Situation Programs: Examples.....	198
10.4	Another Declarative Approach.....	199
10.5	Toward Design Patterns for Context-Aware Applications: Situation Patterns.....	201
10.6	Summary.....	205
	Acknowledgment .....	205
	References.....	205
<b>11</b>	<b>A Future with Aware Systems .....</b>	<b>207</b>
11.1	The Emerging Future: Taking Awareness for Granted.....	207
11.2	Scalability and Usability .....	208
11.3	Final Words .....	209
	<b>Index.....</b>	<b>211</b>

# 1

---

## WHAT IS CONTEXT-AWARE BEHAVIOR?

“Good morning, Smith! Coffee is boiling and your E-newspaper has been downloaded,” a pleasant voice greets you as you walk into the kitchen from the bedroom. As you sit in your car, the seats, mirrors, and steering wheel are automatically adjusted — your son had been using your car last night. In the office, as you sit on the chair in front of your desk, the height of the chair is automatically adjusted — your short colleague had been sitting in your chair, again — and you are automatically logged in to your computer. At lunch time, while in the mall, you are greeted with messages appearing on your smartphone from restaurants serving your favorite Chinese noodles, located no more than 200 m away. Only one’s imagination could limit the possibilities of systems that can be aware of people’s situations or their contexts and do things for them. *The Economist* discusses the sentient office<sup>1</sup> containing technologies that are convivial not only in the office but also at home, “using information about where you are in your home to control the lighting or ensure that only your nearest telephone rings or that the television program you are watching follows you from screen to screen as you move between rooms.” Movies such as *Artificial Intelligence*, *I, Robot*, and *The Matrix* contain futuristic scenarios that, if not going even further beyond, touch the boundaries of what is achievable. But it is not only robots which can have the ability to sense, reason, and act — almost anything can, from the coffee cup, television, soft toys, and the house to the bed.

---

<sup>1</sup> [http://www.economist.com/science/tq/PrinterFriendly.cfm?Story\\_ID=1841108](http://www.economist.com/science/tq/PrinterFriendly.cfm?Story_ID=1841108).

## 1.1 CURRENT COMPUTING TRENDS: FROM THE VIRTUAL TO THE PHYSICAL

Programmers have tremendous power to exert their imagination to create not only office applications but also virtual worlds. From games programming to avatars, virtual environments have become widespread. Recently, increasing attention is being placed on augmenting the physical environment using information technologies. Pattie Maes' *intelligence augmentation*<sup>2</sup> is a phrase used to describe how the physical world can be enriched with intelligent behavior. An area can become an avenue where technologies "pile up" and become interactive (McCullough, 2005) and somewhat aware of their inhabitants, leading to the notion of smart environments, the creation of which has been documented by Cook and Das (2004).

Computer systems that surround, pervade, and intelligently serve people in pleasant and unobtrusive ways provide a vision that has seized the imagination of many. These computer systems might not fit the traditional image of a computer sitting on a desk. Articulation of this vision and its variations has resulted in buzz phrases such as *ubiquitous computing*, *pervasive computing*, *invisible computing*, *the disappearing computer*, *proactive computing*, *autonomic computing*, *ambient intelligence*, and *sensient computing*. But these are not merely phrases; much technology lies beneath the new vocabulary and are being developed under these topics.

- *Ubiquitous computing* (Weiser, 1991)<sup>3</sup> refers to the collective use of computers available in the physical environment of users, perhaps embedded in a form invisible to users. This is the vision of the late Mark Weiser from Xerox PARC for putting computers out into everyday living environments, instead of representing the everyday living environment in the computer.
- *Pervasive computing* refers to the vision of devices or computers pervading lives, as IBM Chairman Lou Gerstner once described: "... A billion people interacting with a million E-businesses with a trillion intelligent devices interconnected." Pervasive computing can be viewed as a combination of mobile computing (use of computers worn on or carried by users) and computers embedded in the fixed environment and so can be understood as another term for ubiquitous computing.
- *Invisible computing* (Norman, 1998; Borriello, 2000) refers to the use of computers in such a way that the task is focused on and facilitated, without too much focus on the tool (i.e., the computer

---

<sup>2</sup> <http://www.kurzweilai.net/meme/frame.html?main=/articles/art0264.html>.

<sup>3</sup> See also <http://www.ubiq.com/hypertext/weiser/UbiCACM.html> and [http://en.wikipedia.org/wiki/Ubiquitous\\_computing](http://en.wikipedia.org/wiki/Ubiquitous_computing).



system) itself. Often, we simply want a task to get done (e.g., get a message to someone), and we might not want to focus on, or wrestle with, the software or the hardware that enables the task. If there is a cognitive burden on the user in employing a tool to perform a task, the more this burden is laid on the task rather than the tool, the better. The overlap with the ubiquitous computing vision is clear; the many computers in the everyday environment that the user might interact with are merely the tools to perform tasks and so should be given only as much attention as a tool deserves.

- The European Union-funded *disappearing-computer* initiative<sup>4</sup> aims to create artifacts commonly seen or used in everyday life with computational capabilities (using some combination of hardware and software) and the ability to work together to produce new behaviors. It also looks at people's experiences with environments comprised of such artifacts. The initiative has a number of projects, including those that explore wearable computer devices and that study how a colocated collection of gadgets might cooperate.<sup>5</sup>
- *Proactive computing* (Tennenhouse, 2000) refers to a focus away from interactivity to computers anticipating user needs and taking action on users' behalf. The idea is that human attention devoted to interaction can be reduced so that users can focus on higher-level tasks.
- Another recent topic is *autonomic computing* (Horn, 2001), which is about building systems that can self-monitor, self-heal, and self-configure. Proactive and autonomic computing overlap, in that they both relate to ubiquitous computing systems and could utilize context information about the environment of the system and users to operate or make decisions. However, they differ in their emphasis on the kind of system behavior to be achieved. A deeper comparison between autonomic and proactive computing is presented by Want et al. (2003).
- *Ambient intelligence* (Marzano and Aarts, 2003) builds on ubiquitous computing and intelligent user interfaces to obtain greater user friendliness and efficient services for users. To quote from *Ercimnews*<sup>6</sup>: "In this vision, people will be surrounded by intelligent and intuitive interfaces embedded in everyday objects around us and an environment recognizing and responding to the presence

<sup>4</sup> See the main Web site for the initiative: <http://www.disappearing-computer.net/>.

<sup>5</sup> <http://www.extrovert-gadgets.net/>.

<sup>6</sup> [http://www.ercim.org/publication/Ercim\\_News/enw47/intro.html](http://www.ercim.org/publication/Ercim_News/enw47/intro.html).

of individuals in an invisible way by year 2010.” Certainly, context-aware computing overlaps with the ambient intelligence vision.

- *Sentient computing* (Hopper, 2000)<sup>7</sup> refers to systems “using sensors and resource status data to maintain a model of the world which is shared between users and applications.” Because such systems try to build a model of a part of the world from sensory information about the user’s circumstances and environment, the idea is very much suggestive of, if not synonymous with, context-aware computing but with an emphasis on the world model.

From the brief description of the topics mentioned, the reader can easily observe the overlap in the technologies they aim to create. Ubiquitous, pervasive, disappearing, invisible, proactive, autonomic, and sentient computers exhibiting intelligent behavior and surrounding the user are a current goal in computing. An aspect of this vision is context-aware behavior in a pervasive computing setting. The next section explores further the notion of context and context awareness.

## 1.2 CONTEXT, CONTEXT AWARENESS, AND SITUATIONS

The notion of context has been observed in numerous areas, including linguistics, philosophy, knowledge representation and problem solving in the field of artificial intelligence, and the theory of communication (Akman, 2002; Bouquet et al., 2003; McCarthy, 1993; Brezillon, 2003). In most work of this nature, context is a key notion (e.g., treated as first-class objects in a logic), and logics have been developed to enable assertions to be made about contexts and allow context to be reasoned about explicitly in knowledge-based systems.

What is context? The *Free Online Dictionary of Computing*<sup>8</sup> defines *context* as “that which surrounds, and gives meaning to, something else.” This definition can be specialized to the application at hand. Whether that “something” is an assertion in a logic, a person, an utterance, or a computer system, with a suitable definition for “meaning,” the intuition captured by the word *context* serves its purpose. Schilit et al. (1994) define context from the perspective of distributed and mobile computing, where a person is that “something,” and *context* refers to information about a person’s proximate environment, such as location and identities of nearby people and objects.

Dey (2001) gives an operational definition of context, which turns out to be very useful in practice and suitable for pervasive computing: “Context

---

<sup>7</sup> See [http://en.wikipedia.org/wiki/Sentient\\_computing](http://en.wikipedia.org/wiki/Sentient_computing).

<sup>8</sup> <http://www.dictionary.com>.