Felicitous Computing

David S. Rosenblum
School of Computing
National University of Singapore
From UCI to NUS
From UCI to NUS
From UCI to NUS
From UCI to NUS
Singapore
Ubiquitous Computing
The Ideal

“The most profound technologies are those that disappear.”
[Mark Weiser, Scientific American, 1991]

Weiser envisioned computing being
“an integral, invisible part of people’s lives”,
where
“the computers themselves ... vanish into the background”
Ubiquitous Computing

The Research Vision
Ubiquitous Computing

The Research Vision
Ubiquitous Computing

The Research Vision
Ubiquitous Computing
The Research Vision
Ubiquitous Computing
The Research Vision
The Reality
Fading into the Background?
The Reality
Fading into the Background?
The Reality

Google Android Market (early 2012)

- The average price of the top 50 paid applications is just US$3.79  [modymi.com]
The Reality
Google Android Market (early 2012)

• The average price of the top 50 paid applications is just US$3.79 [modymi.com]

• 79.3% of paid applications have been downloaded less than 100 times [Distimo]
The Reality
Google Android Market (early 2012)

• The average price of the top 50 paid applications is just US$3.79 [modymi.com]
• 79.3% of paid applications have been downloaded less than 100 times [Distimo]
• Only 0.1% of paid applications have been downloaded 50,000 times or more [Distimo]
The Reality
Stuff Just Doesn’t Work Right
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Engage your customers!
Engage your customers!
Engage your customers!
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Engage your customers!
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Engage your cust
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My Next Appointments Calendar?
Felicitous Computing Institute

Goal:

to realize the original ideals of ubiquitous computing

A new multi-disciplinary research institute hosted in the NUS School of Computing

Strongly driven by challenge problems in a variety of application domains
Felicitous Computing

Definition

Felicitous, adj., well chosen or suited to the circumstances; pleasing and fortunate

[Oxford American Dictionary]

- Computing that is not poorly chosen, ill-suited, displeasing or unfortunate!
- An overarching philosophy of technology development and evaluation
Felicitous Computing
Some Key Elements
Felicitous Computing

Some Key Elements

context-awareness
Felicitous Computing
Some Key Elements

intelligent, unobtrusive processing
Felicitous Computing
Some Key Elements

robustness
Felicitous Computing

Some Key Elements

multi-modal interaction
Felicitous Computing
Some Key Elements

• Beyond these technical characteristics ...

Natural
Useful to Users
Realistic
Beneficial
Felicitous Computing
Current Research Directions

✓ Context-Aware Adaptation
✓ Multi-Modal Interaction
✓ Emotion Sensing and Inference
✓ Software Engineering for Mobile Systems
Two Example Projects

1. Automated Fault Detection in Context-Aware Adaptive Applications (CAAAAs)

2. Context-Aware Mobile Music Recommendation (CAMMR)

✓ Solved problems of both design and robustness

✓ Revealed new, interesting research challenges
CAAAAs
Context-Aware Adaptive Applications
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Context-Aware Adaptive Applications
Adaptation in CAAAs

Adaptation in CAAAs

Adaptation in CAAAs

Adaptation in CAAAs

Adaptation in CAAAs

Adaptation in CAAAs

Adaptation in CAAAs

**Presumed Context**

**Inferred Context**

**Sensed Context**

**Physical Context**

**Application**

**Adaptation Manager**

**Context Manager**

**Middleware**

**Environment**

**Rule Engine**

**3rd-Party Libraries**

Validation of CAAAs

Application

Adaptation Manager

Middleware

Context Manager

Environment

Rule Engine
Validation of CAAAs

Rules are strongly interdependent and have multiple priorities which makes reasoning difficult even for a small number of rules.
Validation of CAAAs

- Application
- Adaptation Manager
- Context Manager
- Middleware

3rd-Party Libraries
Validation of CAAAs

Context is sensed periodically from multiple sources at varying rates.
Approach

1. Derive *Adaptation Finite-State Machine* (A-FSM) from rule logic

2. Explore state space of A-FSM to discover potential faults
   ✓ *Enumerative algorithms*
   ✓ *Symbolic algorithms*

3. (Confirm existence of discovered faults)

PhoneAdapter
PhoneAdapter

- normal, vibrate
- silent, vibrate
- loud, vibrate
- divert to hands-free
- silent, divert to voicemail
- loud, vibrate
PhoneAdapter

- normal, vibrate
- silent, vibrate
- loud, divert to hands-free
- silent, divert to voicemail
- loud, vibrate
PhoneAdapter A-FSM
PhoneAdapter A-FSM

- Jogging
- Outdoor
- Home
- Driving
- Sync
- General
- Meeting
- Office
- Driving Fast

Actions:
- ActivateMeeting
- DeactivateMeeting
PhoneAdapter A-FSM

Global constraints:
- Checking location implies GPS is on.
- Locations are mutually exclusive.
- Speeds monotonically increase.
- A meeting's end time is later than its start time.
Example Faults in PhoneAdapter
Example Faults in PhoneAdapter

User’s phone discovers office PC at home (or vice versa)
Example Faults in PhoneAdapter

Home → General → Office

Nondeterminism!
Example Faults in PhoneAdapter
Example Faults in PhoneAdapter

User leaves home
Example Faults in PhoneAdapter

User starts driving before Bluetooth detects hands-free system
Example Faults in PhoneAdapter

Activation hazard!
Example Faults in PhoneAdapter

Jogging ➔ Outdoor

Outdoor ➔ General

General ➔ Driving

Activation hazard!
Faults in CAAAs

- **Behavioral Faults**
  - Nondeterminism
  - Dead rule
  - Dead state

- **Unreachable state**
- **Activation race**
- **Activation cycle**
Faults in CAAAs

• Behavioral Faults
  - Nondeterminism
  - Dead rule
  - Dead state

• Hazards
  - Hold hazard
  - Activation hazard
  - Unreachable state
  - Activation race
  - Activation cycle
  - Priority inversion hazard
## PhoneAdapter Results

### Behavioral Faults: Enumerative, Symbolic

<table>
<thead>
<tr>
<th>State</th>
<th>Nondeterministic Adaptations</th>
<th>Dead Predicates</th>
<th>Adaptation</th>
<th>Unreachable States</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Races</td>
<td>Cycles</td>
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<tr>
<td>General</td>
<td>37</td>
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<td>45</td>
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<td>Outdoor</td>
<td>3</td>
<td>0</td>
<td>135</td>
<td>23</td>
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<tr>
<td>Jogging</td>
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<td>0</td>
<td>97</td>
<td>19</td>
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<tr>
<td>Driving</td>
<td>0</td>
<td>0</td>
<td>36</td>
<td>13</td>
</tr>
<tr>
<td>DrivingFast</td>
<td>0</td>
<td>0</td>
<td>58</td>
<td>19</td>
</tr>
<tr>
<td>Home</td>
<td>0</td>
<td>0</td>
<td>76</td>
<td>19</td>
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<tr>
<td>Office</td>
<td>0</td>
<td>0</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>Meeting</td>
<td>0</td>
<td>0</td>
<td>32</td>
<td>1</td>
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<tr>
<td>Sync</td>
<td>0</td>
<td>0</td>
<td>27</td>
<td>5</td>
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</tbody>
</table>
### PhoneAdapter Results

**Hazards: Enumerative**

<table>
<thead>
<tr>
<th>State</th>
<th>Context Hazards</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
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<tr>
<td></td>
<td>Paths</td>
<td>Hold</td>
<td>Activ.</td>
<td>Prior.</td>
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<tr>
<td>General</td>
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<td>0</td>
<td>11</td>
<td>3182</td>
</tr>
<tr>
<td>Outdoor</td>
<td>161</td>
<td>0</td>
<td>0</td>
<td>52</td>
</tr>
<tr>
<td>Jogging</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Driving</td>
<td>16</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>DrivingFast</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Home</td>
<td>104</td>
<td>8</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Office</td>
<td>82634</td>
<td>1828</td>
<td>368</td>
<td>2164</td>
</tr>
<tr>
<td>Meeting</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sync</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Rule-based CAAAs can be extremely fault-prone, even with a small set of rules and context variables.

The fault detection algorithms find many actual faults, with different tradeoffs.

Some alternative to rule-based adaptation is needed...
✓ Users’ short-term music needs are driven by their current activity

✓ Fully automated music recommendation requires solving the cold-start problem:
   Which existing user will like a new song?
   Which existing songs will a new user like?

CAMMR
Functionality
CAMMR
Functionality
CAMMR

Functionality
CAMMR
Functionality
CAMMR
Key Characteristics

✓ Real-time sensor-driven activity inference
  Running, Walking, Sleeping, Working, Studying, Shopping

✓ Offline low-level audio content analysis

✓ Personalization of recommendations
CAMMR
Supervised Learning

✔ Machine learning, not handcrafted rules!

Ground truth:

**Activity:** Manually tagged sensor streams

**Music:** Activity-tagged Grooveshark playlists

Coupled with *incremental learning* of individual preferences
CAMMR
Architecture

Back End
Music
Database

Front End

NUS
National University of Singapore
CAMMR

Architecture

Back End

Music Database

Audio Feature Extraction

Binary Classifiers (Adaboost)

Running
Walking
Sleeping
Working
Studying
Shopping

Front End

Mobile Phone
CAMMR
Architecture

Back End
- Music Database
  - Audio Feature Extraction
  - Binary Classifiers (Adaboost)
    - Running
    - Walking
    - Sleeping
    - Working
    - Studying
    - Shopping

Front End
- Sensor Stream Feature Extraction
  - Sensor signal features
CAMMR Architecture

**Back End**
- Music Database
- Audio Feature Extraction
- Binary Classifiers (Adaboost)
  - Running
  - Walking
  - Sleeping
  - Working
  - Studying
  - Shopping
- Classification Results

**Front End**
- Sensor Stream Feature Extraction
- Sensor signal features
- Microphone, Accelerometer and Clock Features

**ACACF**
Probabilistic Graphical Model (Naive Bayes)
CAMMR

Architecture

Back End

Music Database

Audio Feature Extraction

Binary Classifiers (Adaboost)

Classification Results

Recommendation

Front End

Music Play

Sensor Stream Feature Extraction

Sensor signal features

Microphone, Accelerometer and Clock Features

ACACF
Probabilistic Graphical Model (Naive Bayes)
CAMMR
Architecture

Back End
Music Database
Audio Feature Extraction
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Classification Results
ACACF Probabilistic Graphical Model (Naive Bayes)

Front End
Music Play
Recommendation
User Feedback
Sensor Stream Feature Extraction
Sensor signal features
Microphone, Accelerometer and Clock Features

Music&
Database&
Sensor'signal'
features'

Running&
Walking&
Sleeping&
Working&
Studying&
Shopping&

Audio Feature Extraction
Recommendation
User Feedback
Sensor Stream Feature Extraction
Music Database
Binary Classifiers (Adaboost)
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Music&
Database&
Sensor'signal'
features'

Running&
Walking&
Sleeping&
Working&
Studying&
Shopping&
Results
Inter-Subject Agreement on Music Preferences

<table>
<thead>
<tr>
<th>Activity</th>
<th>Kappa Agreement</th>
<th>Percent Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running</td>
<td>0.27</td>
<td>0.35</td>
</tr>
<tr>
<td>Working</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Sleeping</td>
<td>0.29</td>
<td>0.28</td>
</tr>
<tr>
<td>Walking</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Shopping</td>
<td>0.07</td>
<td>0.17</td>
</tr>
<tr>
<td>Studying</td>
<td>0.09</td>
<td>0.11</td>
</tr>
</tbody>
</table>

- 10 subjects
- Manual activity tagging of 1200 Grooveshark and YouTube songs
- $p < 0.0001$
Results

Precision of Activity Inference

<table>
<thead>
<tr>
<th>Activity</th>
<th>AdaBoost</th>
<th>C4.5</th>
<th>LR</th>
<th>NB</th>
<th>SVM</th>
<th>KNN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running</td>
<td>0.974</td>
<td>0.976</td>
<td>0.975</td>
<td>0.841</td>
<td>0.974</td>
<td>0.970</td>
</tr>
<tr>
<td>Working</td>
<td>0.933</td>
<td>0.932</td>
<td>0.921</td>
<td>0.876</td>
<td>0.929</td>
<td>0.922</td>
</tr>
<tr>
<td>Sleeping</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.994</td>
<td>0.999</td>
<td>0.993</td>
</tr>
<tr>
<td>Walking</td>
<td>0.961</td>
<td>0.960</td>
<td>0.955</td>
<td>0.909</td>
<td>0.960</td>
<td>0.953</td>
</tr>
<tr>
<td>Shopping</td>
<td>0.972</td>
<td>0.972</td>
<td>0.948</td>
<td>0.953</td>
<td>0.965</td>
<td>0.955</td>
</tr>
<tr>
<td>Studying</td>
<td>0.854</td>
<td>0.867</td>
<td>0.835</td>
<td>0.694</td>
<td>0.860</td>
<td>0.855</td>
</tr>
<tr>
<td>OVERALL</td>
<td>0.951</td>
<td>0.952</td>
<td>0.941</td>
<td>0.893</td>
<td>0.950</td>
<td>0.943</td>
</tr>
</tbody>
</table>

- 10 subjects, 6 activities, 30 minutes/session
- Naive Bayes provides very good precision and efficiency for smartphones
Results

Precision of Activity Inference

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- 10 subjects, 6 activities, 30 minutes/session
- Naive Bayes provides very good precision and efficiency for smartphones
Results

Retrieval Performance

- Precision@K for top K songs
- Baselines are random rankings
Results

Accuracy of Music Recommendation

1
1.5
2
2.5
3
3.5
4
4.5
5

Average Rating

Traditional (R1)
CAMMR Auto Mode (R2)
CAMMR Manual Mode (R3)

• 10 subjects, divided into experimental and control group
• R2 vs R1: \( p = 0.0478 \)
• R3 vs R2: \( p = 0.1374 \)
• R3 vs R1: \( p = 0.0001 \)
Results

Effectiveness of Incremental Adaptation

- 2 subjects, continuous usage for one week
CAMMR

Summary

✓ CAMMR is the first automated solution for short-term music listening needs

✓ Provides a complete solution to the cold-start problem

✓ Employs machine learning for more robust adaptation
Other Projects

Emotion Sensing

Arousal

Valence
Other Projects

Emotion Sensing

Arousal

+ Valence

-
Other Projects

Emotion Sensing

- Sensing from Mobile & Wearable Sensors
  - **Microphone:** speech
  - **Camera:** facial expressions, eye tracking
  - **Accelerometer:** movement, orientation
  - **MS Kinect:** gesture
  - **GPS:** location
  - **GSR:** skin conductivity
  - **HRM:** pulse
Other Projects

Emotion Sensing

- Many Obstacles and Limitations
  - Lack of empirical evidence for biological signatures of emotions
  - Much variability in experiencing emotions
    - Short-term situations vs. long-term mood
    - Between and within cultures and languages
    - By the same individual
  - Difficulty of inducing spontaneous, genuine emotion in controlled experimental settings
Other Projects

Emotion Sensing

• Research Agenda

✓ Multimodal sensing of core affect
✓ Contextualization of emotion sensing
✓ Computational platform for sensing and processing
✓ Realistic empirical study designs
Felicitous Computing
Software Engineering Challenges
Felicitous Computing
Software Engineering Challenges

“There are known knowns; there are things we know we know. We also know there are known unknowns; that is to say, we know there are some things we do not know. But there are also unknown unknowns – the ones we don’t know we don’t know.”

— Donald Rumsfeld
Felicitous Computing
Software Engineering Challenges

- Validation of ubiquitous computing systems is riddled with **uncertainty**
  - Unpredictable ambient environments
  - Imprecision of context inference
  - Disagreement among users and/or observers
  - Slippery slope between “known unknowns” and faults

- Similar in spirit (but not in character) to Weyuker’s “non-testable programs”

- May need to employ relative quality comparison of systems rather than absolute quality assessment
The technology for felicitous computing is here.

But building felicitous computing systems remains challenging.

We still lack a clear body of design and engineering principles.

At NUS we are pursuing research breakthroughs to make felicitous computing an integrated and invisible part of people’s lives.
Felicitous Computing
David S. Rosenblum
School of Computing
National University of Singapore

Thank you!