The Coming-of-Age of Software Architecture Research

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Executive Summary

- Technical ideas in software engineering evolve in predictable ways
 - This evolution pattern sets expectations for software architecture research
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- **Lessons for developers:** what to expect of software architecture research, now and in the future
 - **Lessons for researchers:** useful research paradigms and validation techniques
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Engineering

Definitions abound. They have in common:

Creating cost-effective solutions ...

... to practical problems ...

... by (preferring to) apply scientific knowledge ...

... building things ...

... in the service of mankind

Engineering entails making decisions under constraints
of limited time, knowledge, and resources

SE research is a prime source of the systematic knowledge
SE research problems should reflect the constraints

Software Architecture Research

Software architecture research is the principled
study of the overall structure of software systems,
especially the relations among subsystems and
components.

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Transition Points for Abstract Data Types

- Basic research ==> concept formation
 - > 1968: formulation of information hiding
- Concept formation ==> development & extension
 - > 1973: abstract data type models
- Development & extension ==> internal exploration
 - > 1977: incorporation in programming languages
- Internal exploration ==> external exploration
 - > 1980: incorporation in other technologies
- External exploration ==> Popularization
 - > late 80's: object models, C++, Java

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Basic Research in Software Architecture

- Architectures for particular product lines or application domains (e.g., oscilloscopes, missile control)
- Catalogs that captured informal use of box and line diagrams
- Key idea: models for architectural style

Late 1980s to 1992/3

Concept Formulation in Software Architecture

- Architecture description languages
 - > capture design abstractions in system definition
 - > exploit properties of particular styles
 - > support style-specific compilation or analysis
- Prototype implementations support further experiments
- Formalization, both within language and standalone
- Catalogs expanded to taxonomies

Mid 1990s and ongoing

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"Software Architecture" citation counts

NEC Bibliography citation counts

"software architecture" in entry (2000 of 3595 citations)

"software architecture" in title (1831 citations)

Falloff in 1997-99 may reflect delay in updating bibliography and/or normal publication lags

Software Architecture 24 Most Cited

- Published 1990-1998
- 4 books (1995-1998)
- 20 papers
 - > 8 architectures for particular domains (1990-1995)
 - > 7 surveys or models for field (1992-1995)
 - > 3 formalizations (1993-1996)
 - > 1 architecture description language (1995)
 - > 1 reverse engineering (1997)

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Development and Extension in Software Architecture

- Unification and refinement
 - > ACME interchange language
 - > refinement of taxonomies
- Maturing institutions
 - > workshops, special issues, conference tracks
 - > books
 - > independent conference

Late 1990s and ongoing

Internal Enhancement and Exploration in Software Architecture

- Architectural styles used informally as design guides
- Some formal analyses of real systems
- Books/courses on software architecture

From 1998 onward

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External Enhancement and Exploration in Software Architecture

- Recognition of the value of architects and architectural design considerations
 - > Processes require architectural design reviews and explicit architectural documentation
 - > Emerging use of product line architectures, commercial architectural standards, component integration frameworks
 - Tool-supported methods
 - > Architectural views in UML
 - > Architectural Tradeoff Analysis Method
- Very late 1990s and ongoing*

Popularization of Software Architecture

- Emerging standards
 - > IEEE-Std-1471-2000, recommended Practice for Architectural Description of Software-Intensive Systems
 - > Standards for particular component families
 - » but these reflect component reuse interests as much as architecture

Just beginning

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Focus on Research

- Recall ...

SE research is a prime source of the systematic knowledge
SE research problems should reflect the constraints

- Turn now to research strategies

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Research Strategy

Examine the kinds of research questions software engineers ask and the ways they study those questions

- Ideas mature over time
 - They grow from qualitative and empirical understanding to precise and quantitative models
- Research questions are of different kinds
 - Kinds of interesting questions change as ideas mature
- Research strategies also vary
 - They should be selected to match the research questions

Research Objectives

Real World
Practical problem

Real World
Solution to practical problem

- Key objectives
 - > **Quality** -- utility as well as functional correctness
 - > **Cost** -- both of development and of use
 - > **Timeliness** -- good-enough result, when it's needed
- Address problems that affect practical software

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Types of Research Questions

- **Feasibility** Does X exist, and what is it ?
Is it possible to do X at all ?
- **Characterization** What are the characteristics of X ?
What, exactly, do we mean by X ?
What are the varieties of X,
and how are they related ?
- **Method/Means** How can we do X ?
What is a better way to do X ?
How can we automate doing X ?
- **Generalization** Is X always true of Y ?
Given X, what will Y be ?
- **Discrimination** How do I decide whether X or Y ?

Examples of Research Questions about Software Structure

- **Feasibility** Is it possible to describe relations among components of a software system?
- **Characterization** What is the important information to share and hide about a component?
- **Method/Means** How can we incorporate abstract data types in a programming language?
- **Generalization** What is a formal relation between the specification of an abstract data type and its implementation?
- **Discrimination** What organization should I choose for a user interface component?

DeRemer/Kron 76, Parnas 72, Liskov&al 81, Wulf &al 76, Hoare 72, Lane 90

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Examples of Software Architecture Research Questions

- **Feasibility** Is it possible to automatically generate code from an architectural specification?
- **Characterization** What are the important concepts for modeling software architectures?
- **Method/Means** How can we exploit domain knowledge to improve software development?
- **Generalization** What patterns capture and explain a significant set of architectural constructs?
- **Discrimination** How can a designer make tradeoff choices among architectural alternatives?

Shaw&al 95; Perry&al 92; Garlan&al 93; Goodwin&al 92; Buschmann&al 96; Kazman&al 99

Research Strategy

Real World
Practical problem

Real World
**Solution to
practical problem**

Research Setting
Idealized problem

Research product
(technique, method,
model, system, ...)

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Types of Research Results

- **Qualitative & descriptive models** Report interesting observations
Generalize from (real-life) examples
Structure a problem area; ask good questions
- **Techniques** Invent new ways to do some tasks,
including implementation techniques
Develop ways to select from alternatives
- **System** Embody result in a system, using the system
both for insight and as carrier of results
- **Empirical models** Develop empirical predictive models from
observed data
- **Analytic models** Develop structural models that permit
formal analysis

Maturity: Kinds of Research Results

Brooks proposed recognizing three kinds of results, with individual criteria for quality:

- > **findings** -- well-established scientific truths --
judged by **truthfulness** and **rigor**
 - > **observations** -- reports on actual phenomena --
judged by **interestingness**
 - > **rules-of-thumb** -- generalizations, signed by an author
(but perhaps not fully supported by data) --
judged by **usefulness**
- with **freshness** as criterion for all

Frederick P. Brooks, Jr. Grasping Reality Through Illusion -- Interactive Graphics Serving Science.
Proc ACM SIGCHI Human Factors in Computer Systems Conference, May 1986, pp. 1-11.

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Examples of Software Architecture Research Results

- **Qualitative & descriptive models** Early architectural models
Architectural patterns
- **Techniques** Domain-specific software architectures
UML to support object-oriented design
- **System** Architecture description languages
- **Empirical models** Communication metrics as indicator of impact on project complexity
- **Analytic models** Formal specification of Higher Level Architecture for simulation

Perry&al 92, Garlan&al 93, Buschmann&al 96, Goodwin&al 92, Booch 98; various; Dutoit&al 98; Allen&al 98

Research Objectives

Real World
Practical problem

Real World
Solution to
practical problem

Research Setting
Idealized problem

Validation Task 1:
Does the product solve
the idealized problem?

Research Setting
**Solution to
idealized problem**

Research product
(technique, method,
model, system, ...)

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Types of Research Validation

- **Persuasion** I thought hard about this, and I believe...
- **Implementation** Here is a prototype of a system that ...
- **Evaluation** Given these criteria, the object rates as ...
- **Analysis** Given the facts, here are consequences ...
 - Formal model Rigorous derivation and proof
 - Empirical model Data on use in controlled situation
- **Experience** Report on use in practice
 - Qualitative model Narrative
 - Decision criteria Comparison of systems in actual use
 - Empirical model Data, usually statistical, on practice

Examples of Software Architecture Research Validation

- **Persuasion** Early architectural models
- **Implementation** Early architecture description languages
- **Evaluation** Taxonomies; performance improvement
- **Analysis** (Many predictive models)
 - Formal model HLA for distributed simulation
 - Empirical model User interface structure
- **Experience** (Many case studies)
 - Qualitative model Architectural patterns
 - Comparison Domain-specific architectures
 - Empirical model Communication and project complexity

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Building Blocks for Research		
Question	Strategy/Result	Validation
Feasibility	Qualitative model	Persuasion
Characterization	Technique	Implementation
Method/Mean	System	Evaluation
Generalization	Empirical model	Analysis
Selection	Analytic model	Experience

A Common Plan		
Question	Strategy/Result	Validation
Feasibility	Qualitative model	Persuasion
Characterization	Technique	Implementation
Can X be done better?	Build a Y	Measure Y, compare to X
Generalization	Empirical model	Analysis
Selection	Analytic model	Experience

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 - > I offer these as **observations**, in Brooks' sense

What Next?

- Software architecture
 - > Don't just continue in the style of the 90's
 - > Make existing results more robust, better evaluated
 - > Address new problems: highly distributed systems, dependability, humane systems
 - > Help transition to practice
- Software engineering
 - > Be more explicit about research paradigms, when and why they work
 - > Be more careful about validation, especially real-world significance