

# Research Methods in Computing: What are they, and how should we teach them?

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## ABSTRACT

Despite a lack of consensus on the nature of Computing Research Methods (CRM), a growing number of programs are exploring models and content for CRM courses. This report is one step in a participatory design process to develop a general framework for thinking about and teaching CRM.

We introduce a novel sense-making structure for teaching CRM. That structure consists of a road map to the CRM literature, a framework grounded in questions rather than answers, and two CRM skill sets: core skills and specific skills. We integrate our structure with a model for the process a learner goes through on the way to becoming an expert computing researcher and offer example learning activities that represent a growing repository of course materials meant to aid those wishing to teach research skills to computing students.

Our model is designed to ground discussion of teaching CRM and to serve as a roadmap for institutions, faculty, students and research communities addressing the transition from student to fully enfranchised member of a computing research community of practice. To that end, we offer several possible scenarios for using our model.

In computing, research methods have traditionally been passed from advisor to student via apprenticeship. Establishing a richer pedagogy for training researchers in computing will benefit all (see Figure 1).

## Categories and Subject Descriptors

**K.3.2 [Computers and Education]:** Computer and Information Science Education—*Computer science education, Information systems education, Literacy*

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**Figure 1: A richer set of options for teaching CRM benefits all the stakeholders.**

## General Terms

Experimentation, Human Factors, Design

## Keywords

Research Methods, Situated Learning, Constructivism, Pedagogy, Learning Activities

## 1. INTRODUCTION

Despite a lack of consensus on the nature of Computing Research Methods (CRM), a growing number of programs are exploring models and content for CRM courses with varying degrees of success [87, 84, 101, 105]. In 2005, the SIGCSE Committee on Teaching Computer Science Research Methods (SIGCSE-CSR) [89] was founded to facilitate collaborative exploration of the content, pedagogy and curricular issues related to teaching CRM. SIGCSE-CSR runs a listserv, sponsors meetings at technical conferences, and hosts a Wiki [88].

On the listserv and at a Birds-of-a-feather (BOF) session at SIGCSE 2006 [41], the most frequently mentioned barriers to establishing a successful course were: (1) not being sure what material to teach, and (2) a lack of resources from which to build

a course. Therefore, SIGCSE-CSRSM sponsored an ITiCSE 2006 working group (WG) on teaching CSRSM tasked to:

1. identify and classify common characteristics of research methods used in various domains of computer science to be used in formalizing a core set of CSRSM, independent of specific domains;
2. develop a basic set of standards for CSRSM literacy (based on the outcomes of the first task); and
3. propose a general framework of learning activities suitable for teaching CSRSM literacy.

The focus of the WG shifted from information transfer to constructing a sense-making structure for CRM as a result of the WG's discovery process preceding ITiCSE 2006 (see Section 1.5.) We also expanded our mission from research methods in CS to research methods in computing as a whole because academic computing programs outside the US do not draw the same distinctions between types of computing degrees, nor do they use the same terminology. We define computing to cover the same broad disciplinary ground as discussed in *Computing Curricula 2005 – The Overview Report* [47]. Thus, throughout this report, we will discuss research methods in computing, not in computer science.

In the rest of this section, we explain our motivation and our frame of reference towards CRM, including a thorough investigation of the previous efforts to define computing research methods. Section 2 introduces a novel sense-making structure for research in computing. That structure consists of a roadmap to the CRM literature, a framework grounded in questions rather than answers, and two key lists of skills for doing quality research: a list of core skills and a list of specific research skills. Section 3 addresses the process a learner goes through on the way to becoming an expert computing researcher. We offer example learning activities that represent a growing repository of course materials meant to aid those wishing to teach research skills to computing students. Section 4 presents sample scenarios describing how different types of institutions might foster research skill development, and suggests what this skills transfer might mean from the viewpoint of students, faculty, and research communities of practice (CoP). Finally, Section 5 discusses where we are in the process and where we plan to go next. Communication requires a common language (syntax) and common understanding of the meaning of that language (semantics). To that end, the paper is augmented with an appendix that includes a table of acronyms used in the article, and an extensive glossary of research terminology gleaned from the literature on research methods from computing. We do not offer these definitions as canonical definitions, but rather as an attempt to foster consensus on the meaning of CRM terminology.

This report is one step in a participatory design process to develop a general framework for thinking about and teaching computing research methods.

## 1.1 Motivation

Most of the sciences and all of the social sciences have formalized discipline-specific bodies of research methods. Such a formalized body of knowledge serves two critical roles: it forms a common ground for researchers in a discipline, and it facilitates training new researchers in a discipline.

In these disciplines, research methods are taught through a combination of laboratory courses, research methodology courses and apprenticeships at both the undergraduate and graduate

levels. Pedagogical materials enable students to study the methodology of a particular type of research, the kinds of data that can be collected, how to collect that data, what analysis can be done on the data to produce meaningful results, and how to interpret those results (see Figure 2). Studying research methods enables all practitioners to assess the quality and claims of published research. Research methodology courses and textbooks are not intended to replace experience for students intending to pursue research careers, but to give them a place to start. Once research students become research faculty, a well-codified research methods corpus enables effective collaboration with and evaluation of faculty in other specialties.

In computer science, research methods have historically been passed from advisor to student via apprenticeship [101, 105]. Most of us learned these methods from a mentor or not at all. Recent years have seen growing interest in a broader pedagogy for teaching CRM [17], for example, by emphasizing the scientific method in existing undergraduate courses [11] or through adding or revising dedicated research methods courses, at both the undergraduate and graduate levels [101, 105].

Exclusive reliance on apprenticeship limits the creative research possible by faculty and students since it hampers our ability to do research outside of our apprenticed area. The traditional dominance of the apprenticeship model may also be a factor in the lack of diversity in computer science, as a successful mentor/protégé relationship requires the mentor to “see themselves” in the protégé. Establishing a richer pedagogy for training researchers in computing will benefit all the stakeholders (see Figure 1).

## 1.2 Trying to define CRM

Although few books exist concerning research methods in computing, many computing disciplines have a rich tradition of journal and conference papers addressing research methods in particular research areas. These papers generally take one of two forms: (1) papers focused on a particular research method (e.g., “An Empirical Evaluation of the G/Q/M Method” [22], “The Applicability of Grounded Theory as Research Methodology in Studies on the Use of Methodologies in IS Practices” [33], or “A Decomposition Model for the Layered Evaluation of Interactive Adaptive Systems” [67]); and (2) papers addressing research methods as a whole in a particular research area (e.g., “Emerging Research Methods for Understanding Mobile Technology Use” [36], “Theories, Methods and Tools in Program Comprehension: Past, Present and Future” [93], or “Methods and Techniques for the Evaluation of User-adaptive Systems” [30]). Some papers do both, e.g., “A Case Study Investigating the Characteristics of Verification and Validation Activities in the Software Development Process” [7].

Emphasis on research methods varies wildly by research area. One view of this variable emphasis is presented in Table 1. Table 1 lists the percentage of the literature indexed in the ACM Guide to the Computing Literature sponsored by each active ACM SIG that is returned on a search on the regular expression “research method”. The ACM Guide indexes a broad set of computing literature beyond the literature published by ACM. Each ACM SIG is a computing research community of practice. The publications sponsored by a SIG are thus the core archival literature of a computing research CoP. Thus, Table 1 presents one measure of the variability in emphasis on CRM that exists among computing research CoPs.

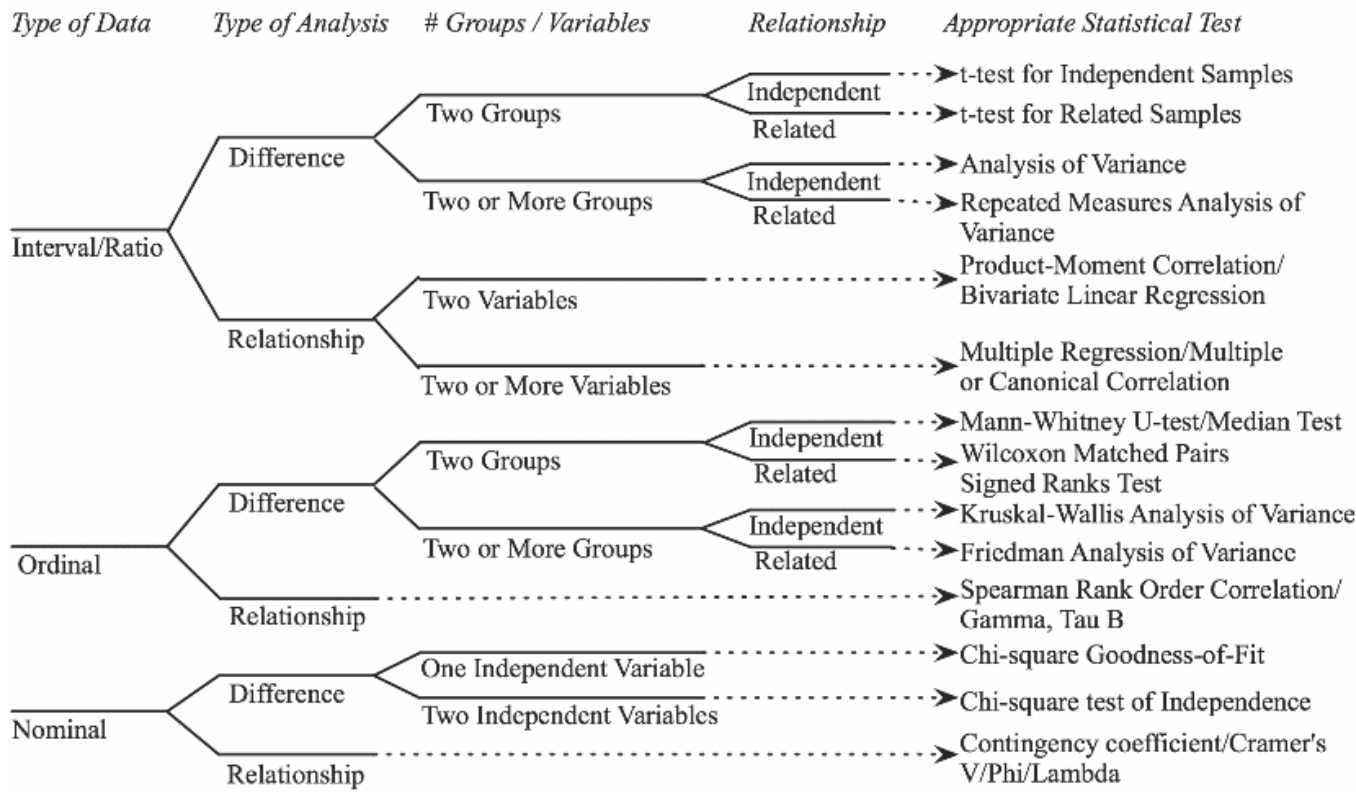


Figure 2: A behavioral science RM handout (after Dr. E. Lea Witts.)

Table 1 only tells part of the story. SIGART's percentage is quite small, for example, yet research methods is sufficiently emphasized in AI to support a dedicated textbook on the subject [14]. SIGGRAPH's percentage is also quite small, yet research methods has been the topic of a series of SIGGRAPH BOFs, and the SIGGRAPH education committee has appointed an official liaison to SIGCSE-CSR.

In our literature review, we found that many computing research CoP tend to publish research methods papers in specialty journals and conference proceedings rather than in major archival journals. These specialty sources are less likely to be included in the ACM Guide to Computing Literature, making much of the disciplinary research methods literature difficult to navigate. While they are generally included in major indices such as Compendex [21], online access to indices such as Compendex is generally prohibitively expensive for non-doctoral granting institutions, as is full-text access to conference proceedings. Students at non-doctoral granting institutions are particularly dependent on the literature for a roadmap to CRM, as their faculty are necessarily less active in research. Thus, those most in need of this literature are those least likely to have access to it, a pattern that is particularly significant from a teaching and diversification point of view.

### 1.3 A CRM taxonomy

Glass, Ramesh and Vessey (GRV), a software engineer, a computer scientist, and an information scientist, respectively,

recently developed a metadata set for research in the computing disciplines [31, 32, 76, 98]. GRV's metadata set consists of multiple taxonomies, one each for topic, research approach, research method, reference discipline, and level of analysis.

GRV developed their CRM taxonomy through a review of the existing literature on CRM, adopting an "all of the above" [98] approach while eliminating categories that appeared to be redundant, e.g., eliminating one set of categories as they were "...similar SE categories specific to methods for experimental or empirical studies" [98]. The resulting CRM taxonomy as published in [31] has 19 categories: action research; conceptual analysis; conceptual analysis/mathematical; concept implementation (proof of concept); case study; data analysis; descriptive/exploratory survey; ethnography; field experiment; field study; grounded theory; hermeneutics; instrument development; laboratory experiment – human subjects; laboratory experiment – software; literature review/analysis; mathematical proof; protocol analysis; and simulation. Several categories initially included such as discourse analysis and meta-analysis appear to have been dropped from the final study. GRV tested the resulting CRM taxonomy on a rich set of papers from the CS, SE and IS literature. The entries were classified by pairs of coders, with a high degree of inter-reader reliability.

**Table 1: CRM as a topic for literature indexed in the ACM Guide to the Computing Literature, by ACM SIG, July 2006. Note that the resulting literature sets are not mutually exclusive.**

<i>SIG</i>	<i>Topic</i>	<i>%</i>
SIGMIS	Management Information Systems	7.2
SIGITE	Information Technology Education	4.7
SIGCHI	Computer-Human Interaction	2.9
SIGDOC	Design of Communications	2.8
SIGACCESS	Accessible Computing	2.6
SIGCAS	Computers and Society	2.2
SIGCSE	Computer Science Education	1.8
SIGWEB	Hypertext, Hypermedia, and the Web	1.5
SIGIR	Information Retrieval	1.3
SIGSOFT	Software Engineering	1.2
SIGGRAPH	Computer Graphics and Interactive Techniques	0.8
SIGUCCS	University and College Computing Services	0.6
SIGKDD	Knowledge Discovery and Data Mining	0.5
SIGmm	Multimedia	0.5
SIGAPP	Applied Computing	0.5
SIGSAC	Security, Audit and Control	0.4
SIGADA	Ada Programming Language	0.4
SIGSIM	Simulation and Modeling	0.3
SIGecom	Electronic Commerce	0.3
SIGMOD	Management of Data	0.3
SIGICE	Individual Computing Environment	0.2
SIGCOMM	Data Communication	0.2
SIGART	Artificial Intelligence	0.2
SIGMETRICS	Measurement and Evaluation	0.1
SIGPLAN	Programming Languages	0.1
SIGMICRO	Microarchitectural Research and Processing	0.1
SIGMOBILE	Mobility of Systems, Users, Data and Computing	0.1
SIGARCH	Computer Architecture	0.1
SIGSAM	Symbolic and Algebraic Manipulation	0.1
SIGOPS	Operating Systems	0.1
SIGDA	Design Automation	0.0
SIGACT	Algorithms and Computation Theory	0.0
SIGBED	Embedded Systems	0.0
SIGEVO	Genetic and Evolutionary Computation	0.0

In [99], Vogel proposes the following criteria for an effective taxonomy of research methods: comprehensiveness (captures the full spectrum), parsimony (contains no unnecessary categories) and usefulness (robust enough to segment the entries in a useful manner). GRV's CRM taxonomy satisfies Vogel's first two criteria, comprehensiveness and parsimony, but has mixed results for the third criterion, usefulness. The taxonomy is useful for IS in that no more than 2% of the entries were placed in any single category, and all but one of the categories were populated. The taxonomy segments SE rather less effectively: while most categories were populated and the largest category contained less

than half of the entries, only 6 of the 19 categories contained more than 2% of the entries each. The taxonomy is not useful for CS: almost 90% of the papers reviewed were categorized as either conceptual analysis/mathematical (73.4%) or conceptual analysis/non-mathematical (15.1%). In [99], Vogel illustrates his criteria with the case of a taxonomy in which one category (of 5) contained 70.1% of the entries – such a category was “...necessary, but in itself insufficiently segmented.” [99]

How do we interpret this result? GRV's methodology was sound, and resulted in effective topic, research approach and level of analysis taxonomies for all three disciplines. Even in retrospect, GRV's decisions to eliminate, include or add categories are understandable, necessary to achieve comprehensiveness and parsimony (see Figure 3).

One explanation for the variable effectiveness of GRV's CRM taxonomy lies in the analysis of the CRM literature presented in Table 1. The SIG with the strongest focus on research methods in its core literature is SIGMIS. IS has a strong tradition of researching research methods, tracing back to Van Horn's 1973 paper, “Empirical Studies of Management Information Systems” [97]. As a result, IS has begun to approach some sort of consensus on terminology and meaning for IS research methods. All of the references listed in Figure 3, except Zerkowitz, were published in IS or IT sources. Thus, MIS terminology dominates GRV's CRM taxonomy.

#### 1.4 Information Transfer vs. Sense-Making

Creating a taxonomy to serve as a metadata set uses an information transfer metaphor for the computing literature. The information transfer metaphor is “...based on trust in science and scientific methods: when something has been investigated, it is known, and this truth can be transmitted to everyone, for their direct benefit, in the form of information.” [96] The less established the methodology of a discipline, the less the information transfer metaphor holds.

In contrast, the constructivist model views the literature as a conversation, the role of which conversation is to create knowledge. When the information transfer metaphor fails, the use of taxonomies of nouns is problematic because such taxonomies neutralize the richness of the conversation by imposing an (artificial) order. The individual CRMs (nouns) are necessary, but not sufficient. In addition to nouns, constructivists suggest a “verbing approach”, i.e., creating a structure that is interactive, engaging both faculty and students as participants in a process [18]. Such a structure that maps “...the relationships between conversations would not only help users to search for information and documents, but also enable them to make better sense of the subject matter the DL deals with” [96].

#### 1.5 Approach

*CSE [Computer Science Education] experts should devote time to analyzing what actually happens in real CoPs, and then to create learning activities that simulate such tasks as well as possible within the constraints of a school. (I emphasize the word simulate, because I want to distance myself from naïve LPP [Legitimate Peripheral Participation] that insists on “real” situations and contexts.) [5]*

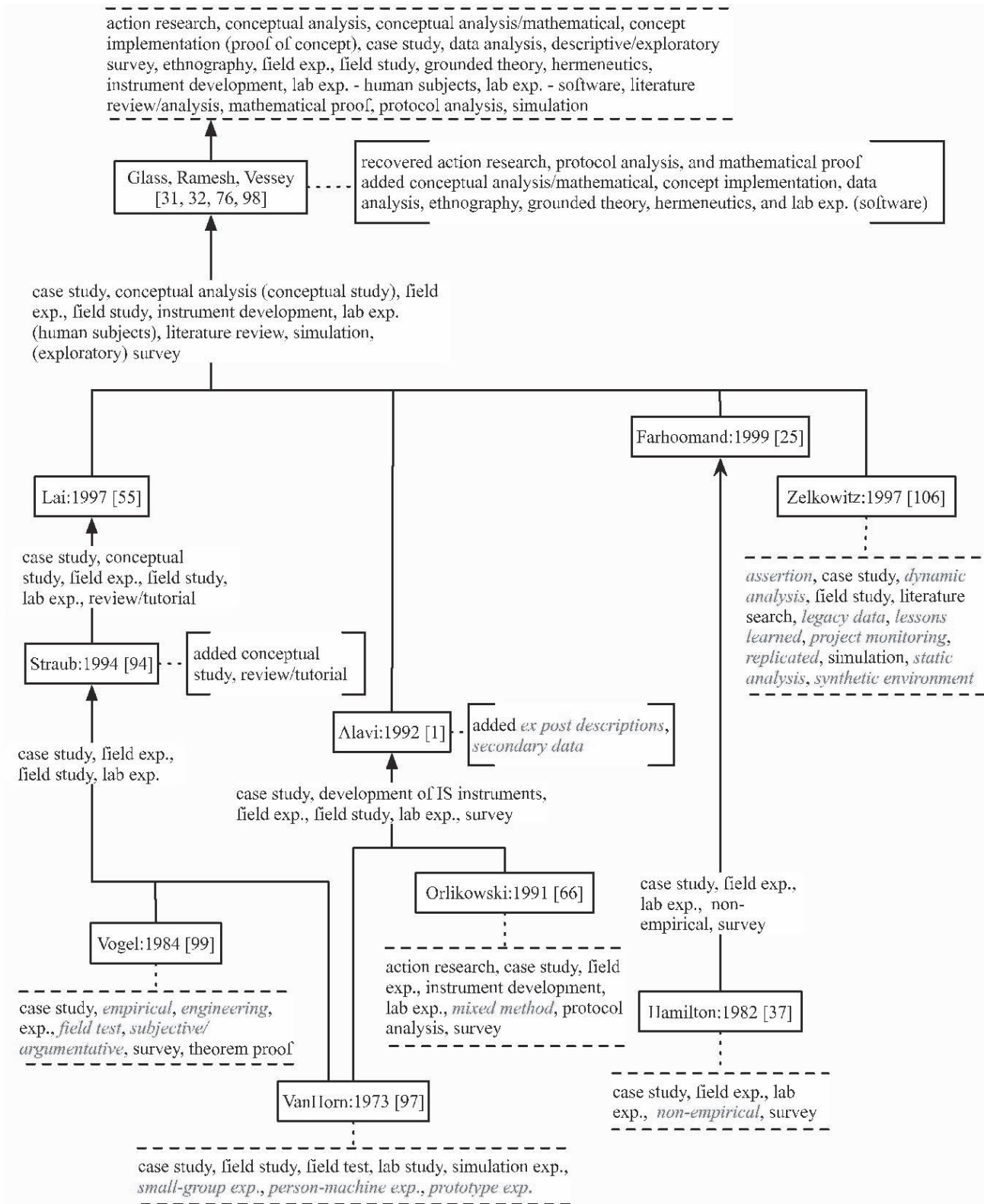


Figure 3: A geneology for Glass, Ramesh and Vessey's taxonomy (exp. = experiments.) The flow of information is from bottom to top. Categories in red (and italic) are categories that were dropped from the final taxonomy. Some redundancies have been eliminated for clarity's sake. For example, [13] was omitted from the figure because the CRM credited to [13], exploratory survey, can be traced to a 1987 study by Farhoomand [24], which is already represented in the figure by Farhoomand [25].

CRM traditionally have been taught via apprenticeship, a form of situated learning. In situated learning, acquisition of knowledge is indivisible from acquisition of identity; one becomes part of a CoP by acquiring requisite knowledge, and, simultaneously, one acquires that knowledge as one becomes part of the CoP [57]. In fact, becoming part of the CoP is necessary to acquiring knowledge. The key to successful situated learning is legitimate peripheral participation (LPP). LPP is peripheral participation that: (1) occurs in context, within the CoP, and (2) is legitimate to both the learner and the CoP. In the ideal, the traditional doctoral candidate/research advisor relationship creates an opportunity for LPP. One can see that LPP is a particularly appropriate model for learning CRM as CRM traditionally has been taught through apprenticeship.

In keeping with our use of the constructivist literature model and situated learning model, our approach is design research. Design research is an emerging educational research approach that is "...iterative, process focused, interventionist, collaborative, ..., utility oriented, and theory driven." [86] Our superstructure, the SIGCSE committee and working group process, is intentionally *iterative* [100]. Rather than establishing standing committees, SIGCSE committees have a fixed lifespan to achieve a concrete goal. Once that lifespan is over, the committee may be reconstituted with new goals, if appropriate. We seek to understand both the *process* by which a student becomes a computing researcher, and the role of CRM related educational artifacts in that process. Our effort is *interventionist* in that a major focus is a coding structure for learning activities intended to facilitate both adoption of new learning activities as well as the reporting of results (see section 3.3). The combination of committee and working group is *collaborative*; SIGCSE committee membership is open. We are decidedly *utility oriented*. This effort grew from a core group of faculty, each engaged in teaching CRM in isolation but interested in improving how their institutions teach CRM. Finally, our effort has been *theory driven* from the start, as we continually link theory to practice through the design of our educational artifacts.

## 2. MAKING SENSE OF CRM

Our goal is to create a structure upon which to build a CRM pedagogy that:

1. supports a distributed locus of control over the definition of CRMs to encourage collaborative sense-making [18];
2. naturally incorporates the existing CRM literature tradition and adapts to future changes in that tradition;
3. is able to incorporate a continuous stream of novel CRMs;
4. and supports a rich set of alternatives for acquiring knowledge of CRM.

We began by collecting the nouns (specific CRM) that form the syntax for our structure (Table 2). We designed a sense-making framework to serve as the global organizing principle (Figure 4). Next, we identified two sets of skills necessary to produce meaningful computing research: *core* skills (Table 3) and

*specific* skills (Table 4). At each step, we asked ourselves two questions:

1. What makes this component specific to computing *research*, as opposed to product development or general problem-solving?
2. What makes this component specific to *computing* research, as opposed to scientific research or, indeed, research in general?

### 2.1 Specific CRM

At ITICSE, the WG held a brainstorming session during which we listed as many specific CRM as we could. Later, we winnowed the list, eliminating redundancies, as well as entries that were classes of research methods (e.g., laboratory experiments) or data analysis techniques (e.g., sensitivity analysis), rather than specific CRM (e.g., simulation.) Winnowing the list was quite difficult, as the lines between a class of CRM, a specific CRM and a data analysis technique are often blurry. Table 2 compares the results of that brainstorming session with GRV's project and the computing literature as a whole. The first column lists the specific CRM. The second column indicates whether the WG listed the CRM during our brainstorming session. If the CRM was mentioned in the literary genealogy for GRV, the third column lists a reference. Otherwise, the last column lists a reference from the computing literature, when we could find one. In combination with the Glossary, Table 2 serves as an entry point in to the conversation on specific CRM in the computing literature.

*What makes the specific CRM specific to computing research?* Many of the CRM listed in Table 2 are not, in fact, specific to computing *research*, but are used in other areas of computing as well. Some of these methods undergo a qualitative shift when used in research, as opposed to development. For example, the nature of the data collected and the data collection mechanisms used in project monitoring differ, depending on the intent of the monitoring. Other disciplines exploit a similar commonality in methodology to teach research across their curriculum, often starting before college.

*What makes the specific CRM specific to computing research?* Again, many of the CRM in Table 2 are not only used in other disciplines, but originate from other disciplines. Often, as a computing research CoP gains experience with a borrowed methodology, computing specific versions will arise. One example is contextual inquiry, which grew out of the ethnographic tradition, but is rooted in practice. One thing that seems, if not unique, at least highly unusual, is the breadth of CRM.

The combination of overlap with computing practice on the one hand, and research in non-computing disciplines on the other hand, may be one cause of the difficulty many faculty feel in designing a CRM curriculum.

### 2.2 A Sense-Making Framework

Our framework (see Figure 4) is grounded in four questions which, collectively, describe the cycle of research. Each question anchors a quadrant in the process of computing research.

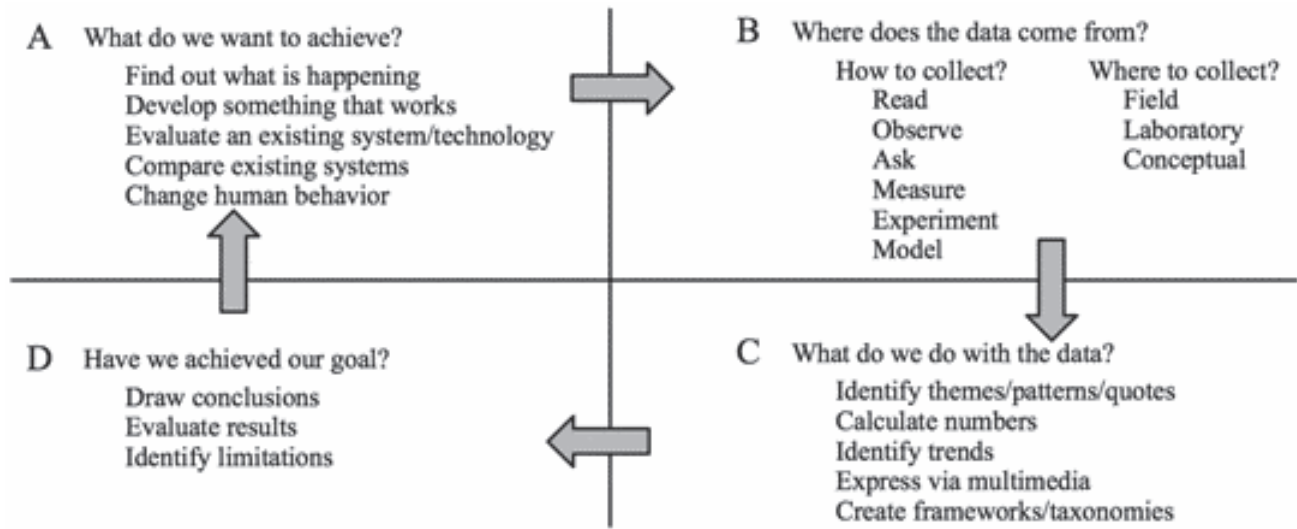


Figure 4: A framework for CRM designed to facilitate teaching.

Here we apply our framework in analyzing an example of typical research in the area of Human Computer Interaction. The paper by Beymer, et al, "Wide vs. Narrow Paragraphs: An Eye Tracking Analysis" [8] demonstrates human factors research and how such research depends on more fundamental investigations in perceptual and cognitive psychology. The paper follows two iterations of our framework.

- A. What did they want to achieve? (Find out what is happening) The authors wished to achieve a better understanding of human behavior when reading columns of text on a computer screen.
  - B. Where did the data come from? (Read) The authors surveyed the early literature by typographers, psychologists, designers, and ergonomists.
  - C. What did they do with the data? (Identify themes) The authors collated the information from the literature, so as to better understand its conclusions. Thus, the first iteration used the specific CRM critical analysis of the literature.
  - D. Had they achieved their goal? (Draw conclusions, identify limitations) The authors now knew a great deal more about human reading of printed material, and online reading, but noted that these prior studies produced contradictory results and used dated technology.
- A. What did they want to achieve? (Compare existing systems) The authors wished to determine whether the length of lines on a web page affects the reading behavior of users.
  - B. Where did the data come from? (Measure, Laboratory) Two conditions (wide columns, narrow columns) were used in a formal experiment, where data on participant eye movement was collected using eye-tracking equipment, and data on comprehension was collected with short multiple-choice tests.
  - C. What did they do with the data (Calculate numbers) They calculated metrics representing the time taken in reading forward, the distance covered in reading forward, eye-velocity, overall elapsed time, overall reading coverage, rate

of re-reading, and time taken in return sweeps. Standard statistical tests were used to determine whether there were significant differences between these metrics for the two conditions. The second iteration was a replicated controlled experiment.

- D. Had they achieved their goal? (Evaluate results, draw conclusions, identify limitations) They were able to make a claim about the different behavior between narrow and wide columns of text. They acknowledged that they were not able to suggest what an optimum width would be, nor were they able to explain why narrower text produced greater retention, even though participants reading the narrow text read less of the content. Both of these outstanding issues could become goals in further iterations of the framework.

The framework is intended primarily as a teaching device, meant to engage faculty and students in a conversation about computing research. Consider a recent MS thesis supervised by one of the authors, "Using Fuzzy K-Modes to Analyze Patterns of System Calls for Intrusion Detection" [34].

- A. What do you want to achieve? (Compare existing systems) Investigate the value of using a more powerful process modeling technique than Stide, an immuno-computing process model based on table lookup.
- B. Where does the data come from? (Measure, Laboratory) Instantiate (implement and tune) a process modeling technique called fuzzy k-modes that clusters categorical patterns of systems calls into centroids and memberships, and test it on a set of artificial and live data published to facilitate just this sort of comparative study, a form of replicated controlled experiment.
- C. What will you do with the data? (Identify patterns, Express via multimedia) Compare the strength of the intrusion detection signals for fuzzy k-modes to those for Stide for string lengths of 6, 10, and 14. Compare rates for detections, false positives and false negatives for artificial and live data for each process in the data set. As no statistical technique exists to evaluate the significance of the results, present the results in a rich series of tables which facilitate visual inspection.

**Table 2: Specific Computing Research Methods.**

<i>CRM</i>	<i>WG</i>	<i>GRV</i>	<i>lit</i>
action research	Y	[31]	
algorithmic analysis	Y		[56]
assertion		[106]	
case study	Y	[1]	
cognitive walkthrough	Y		[102]
concept mapping	Y		[61]
contextual inquiry	Y		[78]
critical analysis of literature	Y	[106]	
design research	Y		[86]
document analysis	Y		[59]
dynamic analysis		[106]	
end-user study	Y		[79]
ethnography	Y		[91]
expert review	Y		[62]
exploratory data analysis	Y		[51]
factorial design	Y	[106]	
field study	Y	[1]	
field tests		[97]	
focus group	Y		[80]
forensic analysis	Y		[70]
grounded theory	Y	[31]	
heuristic evaluation	Y		[65]
interview	Y		[50]
legacy data		[106]	
lessons learned		[106]	
Marco Polo	Y		[71]
mathematical modeling	Y		[28]
mathematical proof	Y	[31]	
maturity model	Y		[43]
meta-analysis	Y		[49]
mixed methods	Y		[58]
narrative analysis	Y		[2]
person-machine experiment		[97]	
pilot testing	Y		[54]
project monitoring		[106]	
proof by demonstration	Y		[73]
proof of principle	Y	[31]	
prototyping	Y	[97]	
replicated controlled experiment		[106]	
risk assessment	Y		[9]
scenario analysis	Y		[92]
semiotics	Y		[3]
simulation	Y	[97]	
small-group experiment		[97]	
static analysis		[106]	
survey	Y	[1]	
synthetic environment exp		[106]	
systemic observation	Y		[45]
taxonomic methods	Y	[99]	
think aloud	Y		[77]
trade-off analysis	Y		[107]
usability testing	Y		[40]
visual proof	Y		[95]
wizard of oz	Y		[16]

D. Have you achieved your goal? (Draw conclusions, Evaluate results, Identify limitations) Results were mixed. For most processes, Stide performed as well as fuzzy k-modes for a substantially reduced computational cost. Fuzzy k-modes performed better on subtle intrusions, possibly because Stide only looks for deviations from what is in its table, while fuzzy k-modes essentially interpolates across the entire string space.

Just as students in the life sciences follow the same general experimental laboratory model throughout their education, so can the four quadrant model also be used to anchor student exercises at any level. Consider an undergraduate exercise requiring students to develop a database embodying a train timetable:

- What do you want to achieve? (Develop something that works) Create a useful train timetable system.
- Where does the data come from? (Read, Ask, Field) Students gather data from all the train timetables they can find, all the relevant maps, and calendars to ascertain weekends and public holidays (a form of document analysis).
- What will you do with the data? (Identify patterns, Express via multimedia) Design an entity relationship (ER) diagram. Once the ER diagram is well defined, students can structure the information into a relational database schema, normalize the schema, and implement the database.
- Have you achieved your goal? (Evaluate results) Students should test the database with relevant, wide ranging SQL queries to determine if they have achieved the goal of the project.

Our framework is general enough that it can be applied throughout the computing curriculum. We can introduce the structure and terminology of this model throughout the curriculum, even if the computing activity that the students are undertaking does not fit the typical definition of “research.”

*What makes the framework specific to computing research?* The framework structures computing from a research viewpoint. As illustrated in the database exercise described above, it can be applied to computing at any level; however, the structure reflects a research bias.

*What makes the framework specific to computing research?* The questions themselves apply to any kind of research. The answers and, particularly, the breadth of the answers, are what characterize the research or project described as computing.

### 2.3 Research Skills

After developing the framework during our discussions, the WG turned our attention to identifying the skills needed to carry out a research project in a sub-discipline. We developed two sets of skills: core (Table 3) and specific (Table 4).

Core skills are foundational. They are characterized by not being localized to specific quadrants or to a particular computing discipline. We identified and populated four types of core skills: organizational, expressive, cognitive and meta-cognitive (see Table 3). The nature and content of the first two categories started from a review of the literature on teaching CRM, the latter from the literature of the development of computing expertise.

Under *organizational*, drawing on our experience with our students, as well as our own experience as research students, we included record keeping and time management. Record keeping includes all forms of record keeping, from keeping track of which



version of code produced which set of data produced which results, through keeping track of where information and ideas can be found in the literature. Time management was a late addition; however it is one that has been “make-or-break” in our experience. Conducting a successful research career requires well developed short-term and long-term time management skills, e.g., to manage several concurrent research projects in varying stages of development.

**Table 3: Core Skills**

Organizational	record keeping time management
Expressive	oral written graphical algorithmic
Cognitive	analysis synthesis evaluation melioration computation
Meta-cognitive	reflection self-regulation monitoring

Under *expressive*, we concluded that oral, written and graphical modes of expression were fundamental to CRM, in contrast to, for example, expression through movement or video. To those three, we added another mode specific to computing, expression via algorithm (see also [44, 64]).

In developing a set of core cognitive skills, we were guided by two seminal papers that address the intersection of computing and cognition: Passig’s *A Taxonomy of Future Higher Thinking Skills* [69] and Denning’s *Great Principles in Computing Curricula* [17]. Passig extends Bloom’s taxonomy [10] with an additional information-age skill, melioration, “the skill of selecting the appropriate amalgam of information and applying it to a solution of problems in situations, which arise at different times and places, thereby meliorating the amalgam.” [69] We skipped the first three levels of Bloom’s taxonomy: knowledge, comprehension, and application, as being in no way specific to research. That left us with the top three levels of Bloom’s taxonomy: analysis, synthesis, and evaluation, plus melioration (see the Glossary for formal definitions of analysis, synthesis, and evaluation). Even with melioration, we concluded that we were still missing a foundational cognitive computing skill, the ability to think in terms of computation. In discussing the role of abstraction in computing, Denning states “In computing we design *abstract objects* that *perform actions*. Other fields use abstraction to explain or to organize tangible objects” [17]. At a loss for a better word, we termed the ability to cognitively manipulate active abstract objects *computation*.

The last category, *meta-cognitive* skills, addresses one of the core characteristics of an expert researcher, that of being an expert learner. An expert learner uses cognitive strategies to organize and integrate information in a way that facilitates true understanding of the content they are learning. “It is the monitoring and self-regulatory skills that enable experts to know not only *what* is important (declarative knowledge) but also *how* (procedural knowledge), *when*, *where*, and *why* (conditional

knowledge) to apply the right knowledge and actions” [23]. Self-regulation is the process by which the expert learner plans, monitors, and evaluates a learning task. The process is both cyclic and recursive.

**Table 4: Specific Research Skills**

#	Specific Skill	Quadrant
1	Search Literature	A
2	Scan Papers	A
3	Select Papers	A
4	Analyze Literature	A
5	Critique Literature	A
6	Analyze Research	A
7	Critique Research	A
8	Formulate Research Questions	A ⇒ B
9	Identify Ethical Concerns	A, B, C
10	Choose Methodology	A ⇒ B ⇒ C
11	Write Research Proposal	A ⇒ B ⇒ C
12	Collect Data	B
13	Verify Data	B
14	Analyze Data	C, D
15	Evaluate Results	D
16	Draw Conclusions	D
17	Identify Limitations	D
18	Link Research to Body of Knowledge	D ⇒ A
19	Connect Theory to Practice	A ⇒ B ⇒ C ⇒ D
20	Present Results: Oral	D
21	Present Results: Written	D
22	Present Results: Other	D

*What makes the skills specific to computing research?* Many of the skills are also necessary for computing practice, although not at as advanced a level, e.g., written expression. The exception are the meta-cognitive skills. These skills, while no doubt *advantageous* for computing practice, are only *required* for computing research. Indeed, the need to “learn how to learn” is the basis for an undergraduate research methods course at University of Mary Washington [74].

*What makes the skills specific to computing research?* Under core skills, algorithmic expression and computation are specific to computing. On the surface, the specific skills are skills needed for research in any scientific discipline. The difference lies in the details, e.g., navigating the computing literature is far more complex than navigating the literature in other disciplines.

## 2.4 Evaluation

We validated the framework and the distinction between core and specific skills by tying the specific skills back to the activities in the framework quadrants. This relation is shown in the third column of Table 4.

For example, knowing how to Search Literature is a necessary skill for the quadrant A activity Find out what is happening. Some of the skills are transitional in nature. Students who can Formulate Research Questions will answer the Quadrant A question “What do we want to achieve?” in formal language and usually answer the Quadrant B question “Where does the data come from?” as well during the process of phrasing the research

question. We show this in Table 4 by drawing an arrow from A to B.

Skills that are not transitional but, rather, are used in multiple places during a research project are simply listed with commas between them. For example, the ability to Identify Ethical Concerns could arise in Quadrant A, Quadrant B, and Quadrant C, depending on the project being undertaken.

The cyclic nature of the framework, indeed of most research, is evident when we Link Research to Body of Knowledge, which, in many circumstances, takes the conclusions from one study (investigated in Quadrant D activities) and drives a new question to be asked in Quadrant A, beginning the cycle again.

### 3. TEACHING CRM

We now consider the process a student must move through to become an expert computing researcher. We begin by presenting a five stage model for the acquisition of skills. Next, we define four learning contexts for moving students toward becoming experts. Finally, we present a coding structure for learning activities that integrates our process model with our sense-making structure, and offer example learning activities that represent a growing repository of course materials meant to aid those wishing to teach research to computing students.

#### 3.1 The Transition from Novice to Expert

To move from novice to expert, a student moves through 5 predictable stages: novice, advanced beginner, competent, proficient, and expert [20]. These stages are named according to how the student consciously or unconsciously processes information. The 5 stages represent a continuum from “knowing that” through “knowing how” to “meta-knowing”.

Initially, the *novice* processes information by identifying facts and features to which rules are applied. With the accretion of experience, she is able to consider context in addition to facts and features. At this point, she also uses more sophisticated rules. These attributes demonstrate the progression to *advanced beginner* status. As experience increases, our student begins to draw conclusions from differing constellations of elements. The process of reaching these conclusions moves through a “what-to-do” list, however, signifying that she is still grounded in “knowing that.” Construction of a constellation of elements denotes the transition from advanced beginner to that of *competence*.

The fourth level finds the *proficient* practitioner. Here, our student is no longer consciously sequencing data through rules. Yet this level denotes a person who is capable of experiencing the task from a specific perspective only. At the proficient level, no detached choice or deliberation occurs. At the final stage, our new *expert’s* knowledge has been consolidated. She knows what to do based on practice and a mature understanding. She is no longer limited in perspective and is able to make detached, deliberate choices without consciously processing data.

#### 3.2 Learning Context

Introducing students to CRM and fostering their skills development from novice to expert can take place in four different contexts:

1. **Master/apprentice:** Master/apprentice is the most commonly used context for teaching CRM [101,105]. This context is a one-to-one relationship, where a supervisor guides a student through the process of a research project, introducing and teaching research methods on the way, and providing continual, personalized feedback on the student’s progress. The student applies the methods taught within the context of his own research project.
2. **Studio:** An extension of the master/apprentice context, the studio is a one-to-few model that is less common than master/apprentice. Studio allows research supervisors to teach research methods to their students in a small group teaching format. Thus, a supervisor may meet with all her research students in sessions whose sole purpose is to focus on research methods. These sessions differ from student talks or research group talks, which focus on the research context of particular projects rather than on methods. Regardless of individual projects, the students can apply these methods to their own contexts.
3. **Dedicated:** Neither master/apprentice or studio are efficient in that faculty teach the same materials to each student one at a time [26, 105]. In contrast, dedicated CRM courses can be attended by many students. This one-to-many model entails defining course content that is taught independent of any particular research project or any particular research supervisor. The students may or may not have already started a research project, and they may have very different interests. Such a course could, in practice, be taught at any level in a computing curriculum.
4. **Embedded:** One of the problems with the dedicated teaching method is that it is seen as an “add-on,” typically at the end of three or four years of computing study. Through embedded teaching, CRM can be taught implicitly within computing courses that explicitly teach other computing topics. This method is therefore many-to-many; many lecturers teach many students during their computing program. Additionally, research methods are introduced in context. Thus, a module in operating systems might include learning activities that require the use of research methods, even though the students may not realize it. Making the research process explicit in such modules may assist students in recognizing the importance and usefulness of following a clearly defined research approach, and would mean that students who carry on to do research in later years are familiar with the approach and terminology and can reactivate that knowledge easily.

#### 3.3 Learning Activities

Since the development of a repository for classroom activities for teaching CRM was one of our original goals, we devised the coding structure for activities described in Table 5. Currently, the coding structure is housed on the CSRW Wiki and linked to more detailed course materials related to the individual assignments housed in the repository.

**Table 5: Coding Structure**

Activity	A short description of the learning activity
Skills	A list of the specific skills from Table 4 addressed. Skills listed in parenthesis are emergent skills rather than the skills that the activity focuses on developing
Students	The number of students involved and their development level (Novice, Advanced beginner, Competent, Proficient, Expert)
Time	The amount of time required in hours in class and out of class
Assessment	A rubric for grading the assignment
History	The number of times and in what context the activity has been used successfully
Feedback	An open prompt for comments, suggestions, frustrations, etc.

To construct the coding structure, we chose several activities used successfully by WG members, and identified: the skills that each activity required, developed, or reinforced; the amount of in-class or out-of-class time each activity required; and in what context the activity has been used. As assessing decontextualized CRM learning activities is a frequent concern, we included a field for how the activity is assessed. We considered including whether the activity was intended for undergraduate students, Masters students, etc., but rejected the idea due to international variability in higher educational structures. Instead, we decided to try coding activities by the median level of the students' skill development in the target skills. Three sample activities are shown in Figure 5 (the feedback column, present on the Wiki, is not shown in the table for brevity's sake.)

Activity: Given examples of good and bad literature reviews, identify process and evaluate product in each case.				
<i>Skills</i>	<i>Stud.</i>	<i>Time</i>	<i>Assessment</i>	<i>History</i>
4, 6, 17, (14), (15), (16)	3, A	3, in class	none	dedicated, 10 times, 1 faculty
Activity: Conduct a literature review to identify gaps in the chosen field. Present written and oral reports.				
<i>Skills</i>	<i>Stud.</i>	<i>Time</i>	<i>Assessment</i>	<i>History</i>
1, 2, 3, 4, 6, 12, 14, 15, 16, 17, 18	3, A	40, out of class	selection (.2), analysis (.4), synthesis (.2), conclusions (.2)	dedicated, 11 times, 1 faculty
Activity: Maintain a research journal.				
<i>Skills</i>	<i>Stud.</i>	<i>Time</i>	<i>Assessment</i>	<i>History</i>
8, 15, 17, (4), (5), (6), (7)	1, A-E	2+ per week, out of class	pattern of use	dedicated, 20+ times, 4 faculty

**Figure 5: Example Activities**

## 4. SCENARIOS

The discussion on the SIGCSE-CSRM listserv [90] makes it clear that a rich pedagogy is needed for teaching CRM. Presently, institutions, faculty, students and research CoPs may view teaching CRM very differently. Healthy dialogue among these shareholders will support the development of a mature CRM corpus. To stimulate discussion, we present a series of scenarios describing how various institutions, faculty, students, and research CoPs could use our structure.

### 4.1 Institutional View

As with other aspects of the computing curricula, one model will not fit all institutions. Ideally, each institution would ascertain whether and how they address core and specific skills and then share their understandings through the listserv, the Wiki and, of course, the computing literature.

#### 4.1.1 Doctoral Universities in the US

Doctoral Universities within the United States offer the richest opportunity for students to participate in ongoing research projects in tandem with their course work. A dedicated course offered to advanced undergraduates and beginning graduate students would complement the existing master/apprentice model for the graduate students as well as offer undergraduates an opportunity to broaden their skills. Undergraduates taking the course before or during a capstone project would gain a higher quality capstone experience. Graduate students taking the course would be establishing the foundation for later research experience under a faculty advisor. Faculty advisors would not have to teach common skills to their research students one at a time. Experience suggests that some aspects of the research flow more smoothly from this preparation [84, 101].

#### 4.1.2 Graduate Institutions in the US

The US has a rich set of institutions that offer a MS in computing, but not a PhD. Computing MS programs at these institutions attract many students interested in switching fields, and as such offer a much needed opportunity to diversify the computing research community. A dedicated course required of all MS students, and elective for undergraduates, would expose many students to computing research who might otherwise never consider research careers. One of the author's institutions, a graduate institution, has successfully used a dedicated CRM course to foster a dynamic student research environment, and now sends many students on to top doctoral programs across the US and beyond.

#### 4.1.3 Liberal Arts Colleges in the US

Liberal Arts colleges in the United States tend to have small departments, limiting the number of courses offered. This environment may leave no room in the curriculum for a dedicated course without eliminating existing courses or creating a faculty overload. Embedded teaching activities leverage the existing curriculum, maintaining an even faculty workload while enriching all students' learning and possibly encouraging a more diverse set of students to pursue computing research careers.

#### 4.1.4 Tertiary institutions outside the US

Outside the US, there are a variety of tertiary education institutions (TEIs). Some countries, e.g., Australia and the United Kingdom, apply the term "university" to a whole range of institutions, some primarily focused on research, others primarily focused on teaching, and many with a dual focus. Other

countries, e.g., New Zealand and South Africa, have a two-tier system of “universities” (primarily focused on research) and “institutes of technology” or “polytechnics” or “technikons” (primarily focused on teaching). The same names may even have different meanings in different countries. For example, institutes of technology in India are very much elite institutions whereas institutes of technology in New Zealand cater for sub-degree students in trades areas as well as degree students in areas such as business, computing, design and health.

This diversity makes it difficult to generalize about TEIs outside the US. However, the three authors based outside the US were able to draw on their experience of TEIs in Australia, Fiji, India, Israel, Malaysia, New Zealand, Papua New Guinea, Singapore, South Africa and the United Kingdom in contributing to the development of the frameworks presented in this paper and can confirm that the variety of approaches espoused in this paper would be effective in a wide range of institutional contexts.

## 4.2 Faculty View

While the framework will not make it possible for an educational psychologist to do operating systems research without the help of an expert, it may facilitate the transition between computing specialties for a computing faculty member. For computing faculty at small colleges where teaching is the primary focus, our approach facilitates mentoring of student-driven research in novel domains.

## 4.3 Student View

From the student perspective, the four-quadrant framework should make the process of learning how to conduct research almost transparent. Since the framework can be applied to non-research topics in early courses, by the time the student has gained maturity in the computing discipline, she will have become so used to the process that the fact that she is conducting *real* research may come as a bit of a surprise. The “*I can do this!*” realization in a junior or senior level course could well make the difference between the vocational choices a student makes after graduation or retention into graduate computing.

## 4.4 CoP View

As indicated in Section 1.2, computing research CoPs appear to vary greatly in the emphasis they place on research methods and may overlap in their interests. The combination of uneven emphasis and overlap can lead to such problems as fragmentation, overlooking gaps, use of conflicting terminology, and expression of contrary views. Perhaps SIGCSE-CSRSM can play a constructive role in this area by fostering consistency and coherence. Since ITiCSE, we have emphasized interaction with other computing research CoP, yielding initial results with SIGGRAPH and the Council on Undergraduate Research.

## 5. DISCUSSION

This paper presents the efforts of ITiCSE 2006 Working Group1, *Research Methods in Computer Science – What are they, and how should we teach them?* The Working Group was an outcome of one of the primary goals of the SIGCSE Committee on Teaching Computer Science Research Methods, that is, to further solidify formalization of Computing Research Methods and foster discussion on how, when, and where to teach them in the computing curriculum. The effort to identify CRM and discuss how they might be taught has many levels of importance. Formalizing CRM creates a common ground for computing

researchers. Of equal importance, formalizing CRM facilitates the training of the next generation of computer researchers.

Researching literature references and finding definitions for the CRM terms in Table 2 took well over 20 hours (of author time, not graduate student time). We were shocked at how difficult it was to find definitions for many of the terms. Few papers give a definition, or even a reference, for the CRM used in the paper. Papers in the life sciences also do not give definitions or references for research methods. However, in life sciences the reader can reasonably be expected to have learned the meaning in a research methods course. Thus, while it is understandable that computing research papers frequently omit any definitive information on CRM, the impact of this omission on young researchers cannot be overestimated. If the WG had to dig this hard to find definitions for CRM, imagine how lost a beginning research student must feel!

Defining and embracing active research across the computing curriculum helps students link computing theory to computing practice and signifies that computing education is maturing as a discipline. While the results of practical investigation of a few of the relevant facts presented in undergraduate courses (e.g., the relative efficiency of different sorting algorithms on different sized arrays) would not be unique or earth-shattering for computing as a whole, the process of understanding the testbed, writing the program, collecting the data, analyzing the data, and writing up the results in a professional format would bring insight into the process of research and effectively link theory to practice for the students. They would, in fact, be replicating real research and coming to the same conclusions presented in class. In this example, the process is more important than the results; in fact, more important than the content of the final written paper.

Undergraduate and secondary school research experience has been shown to be instrumental to retaining students in a variety of scientific disciplines including computer science [39, 48, 81]. Only a small fraction of those who consider pursuing research careers in computing win positions in computing REU (Research Experiences for Undergraduates) programs or are fortunate enough to have close ties with a college that involves secondary school students in computing research. An excellent CRM course or embedded activity has the potential to reach a far wider audience and have a significant impact on recruiting and retaining first-rate computing students.

Members of SIGCSE-CSRSM are now pursuing three parallel efforts that are based on the work presented in this report:

1. disseminating the framework and getting feedback from people adopting the framework;
2. annotating, organizing and expanding the results from our literature search into an annotated bibliography for online publication to be a reference for faculty and students exploring CRM; and
3. exploring the relationship between CRM as a whole and CRM in specific CoPs such as SIGGRAPH.

By creating a codified corpus of CRM through the participatory method, all voices are heard and disparate views given reflective consideration. Thus will our field mature and take its place in the halls of respected science.

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## 8. APPENDIX

### A. TABLE OF ACRONYMS

ACM	Association for Computing Machinery
AH	Adaptive Hypermedia and Adaptive WebBased Systems
BOF	Birds of a feather
CoP	Community of Practice
CRM	Computing Research Methods
CSE	Computer Science Education
CSRM	Computer Science Research Methods
DL	Digital Library
ER	Entity Relationship
GRV	Glass, Ramesh and Vessey
IS	Information Science
LPP	Legitimate Peripheral Participation
REU	Research Experiences for Undergraduates
SE	Software Engineering
SIG	Special Interest Group
SQL	Structured Query Language
TEI	Tertiary Education Institution
UM	International Conference on User Modeling
UMUAI	User-Modeling and User-Adapted Interaction
WG	Working Group

### B. GLOSSARY

- Action Research:** “a specific research approach in which the researcher generates new social knowledge about a social system, while at the same time attempting to change it.” [53]
- Algorithmic Analysis:** “an important part of a broader computational complexity theory, which provides theoretical estimates for the resources needed by any algorithm which solves a given computational problem.” [103]
- Analysis** (in Bloom’s Taxonomy): “A thorough study to comprehend the structure of the learned content, its formal and logic way of organization, in order to detect the elements, outlooks, and methods this content is based upon.” [69]
- Assertion:** “There are many examples where the developer of a technology wishes to show that it is effective and becomes both the experimenter and the subject of the study. ...As skeptical scientists, we would have to view these as potentially biased since the goal is not to understand the difference between two treatments, but to show that one particular treatment (the newly developed technology) is superior.” [106] *see also Subjective/Argumentative*

### Case Study:

- “Single Case: examines a single organization, group, or system in detail; involves no variable manipulation, experimental design or controls; is exploratory in nature.
- Multiple Case Studies: as for single case studies, but carried out in a small number of organizations or context.” [1]

**Cognitive Walkthrough:** “a form and task-based methodology, whereby a task is evaluated by completing a set of forms, each form comprising several evaluation steps. Each step, in turn, is designed to address underlying theoretical concepts through a list of questions to be asked about the interface.” [102]

**Concept Implementation:** “implementation of a system, as in proof of concept” [98]

**Concept Mapping:** “a structured conceptualization process relying on multivariate statistical analysis techniques.” [61]

**Conceptual Analysis/Mathematical:** “[...] [was added] to facilitate the classification of research that utilizes mathematical techniques.” [98]

**Contextual Inquiry:** “a qualitative data-gathering and data-analysis methodology adapted from the fields of psychology, anthropology, and sociology [that] consists of observing and talking with users in their workplaces as they do real work.” [78]

**Controlled Method:** “provides for multiple instances of an observation in order to provide for statistical validity of the results. This is the more classical method of experimental design in other scientific disciplines. We consider four such methods: Replicated, Synthetic environment, Dynamic analysis, and Simulation.” [106]

**Critical Analysis of the Literature:** An appraisal of relevant published material based on careful analytical evaluation.

**Critical Studies:** “aim to critique the status quo, through the exposure of what are believed to be deep-seated, structural contradictions within social systems, and there-by to transform these alienating and restrictive social conditions.” [66]

**Descriptive Research:** “where theories or models are developed and described to provide the input for developing units of the theory, its laws of interaction, system states, and model boundaries.” [63]

**Design Research:** is an emerging educational research approach that is “...iterative, process focused, interventionist, collaborative, ..., utility oriented, and theory driven.” [86]

**Developmental Research:** “involving generating knowledge for explaining or solving general problems.” [63]

**Document Analysis:** “includes examination of system software and documentation, project technical papers and memoranda...” [59]

**Dynamic Analysis:** “The given product is either modified or executed under carefully controlled situations in order to extract information on using the product. Techniques that employ scripts of specific scenarios or which modify the source program of the product itself in order to be able to extract information while the program executes are both examples of this method.” [106]



- Empirical:** “captures the essence of research relying on observation.” [99]
- End-user Study:** a technique for gathering information about the potential use of a system whereby the actual end-users of the system participate in its evaluation.
- Engineering:** “captures MIS research dealing with the application of science and mathematics.” [99]
- Ethnography:** an information gathering technique whereby work is studied “as it actually happens in its real-world setting.” [6]
- Evaluation** (in Bloom’s Taxonomy): “Judging the values in the ideas through use of standards of estimations, that will determine the accuracy level, purposefulness and practicality of the details.” [69]
- Evaluative Research:** “involving methodologies that employ the scientific method, and usually consisting of theory or model generation or observation followed by hypothesis generation and testing.” [63]
- Expert Review:** “is an evaluation method in which experts role-play less experienced users in order to identify usability problems.” [75]
- Exploratory Data Analysis:** “a data-driven search for statistical insights and models” [51]
- Exploratory Survey:** “was added to aid in the classification of research that is based on conducting an ‘exploratory field study in which there is no test of relationships between variables’ [35]” [98]
- External Validity:** “asks the question of *generalizability*: To what populations, setting, treatment variables, and measurement variables, can this effect be generalized?” [12]
- Factorial Design:** “We have maximal local control by applying every possible treatment for each factor. Thus if there are three factors to evaluate, and each has two possible values, then we need to run six experiments, with subject randomly chosen from among the factors.” [106]
- Field Experiment:** “as for laboratory experiment, but in a natural setting of the phenomenon under study.” [1]
- Field Study:** “no manipulation of independent variables, involves experimental design but no experimental controls, is carried out in the natural settings of the phenomenon of interest.” [1]
- Field Tests:** “examination of one or more organizations with respect to one or more variables with a specific experimental design and controls.” [97]
- Focus Group:** a requirements gathering technique whereby “a group of people are posed questions by facilitators and encouraged to react to each other’s comments.” [6]
- Forensic Analysis:** “the application of computer investigation and analysis techniques to gather evidence suitable for presentation in a court of law. The goal of computer forensics is to perform a structured investigation while maintaining a documented chain of evidence to find out exactly what happened on a computer and who was responsible for it.” [83]
- Formulative Research:** “involving development and refinement of theories, models, or frameworks that govern research activities and support scientific progress through paradigm shifts.” [63]
- Grounded Theory:** “[aims] to develop a theory from data rather than gather data in order to test a theory or hypothesis. This means that qualitative methods are used to obtain data about a phenomenon and that a theory emerges from the data.” [33]
- Heuristic Evaluation:** “is an informal method of usability analysis where a number of evaluators are presented with an interface design and asked to comment on it.” [65]
- Historical Method:** “collects data from projects that have already been completed. The data already exists; it is only necessary to analyze what has already been collected. ...There are four such methods: Literature search, Legacy data, Lessons learned, and Static analysis.” [106]
- Influence:** “We need to know the impact that a given experimental design has on the results of that experiment. We will call this *influence* and classify methods as being *passive* or *active*. Passive methods view the artifacts of study as inorganic objects that can be studied with no effects on the object itself. Active methods are those which interact with the artifacts under study.” [106]
- Internal Validity:** “is the basic minimum without which any experiment is uninterpretable: Did in fact the experimental treatments make a difference in this specific experimental instance? ...these variables, if not controlled in the experimental design, might produce effects confounded with the effect of the experimental stimulus.” [12]
- Interpretive Studies:** “assume that people create and associate their own subjective and intersubjective meanings as they interact with the world around them.” [66]
- Interval Measurement:** “is possible when the differing levels of an attribute can be identified, and **equal distances** between the levels of the attribute can also be identified.” [85] Note: Likert scales are treated as interval data.
- Interview:** “an information gathering technique whereby people are posed questions by an interviewer; these interviews may be structured or unstructured.” [6]
- Laboratory Experiment:** “manipulates independent variable; controls for intervening variables; conducted in controlled settings.” [1]
- Laboratory Studies:** “examination of computer-organization problems within a research goal setting of acquiring knowledge that is separate and distinct from the normal operational goals of the organization under study.” [97]
- Legacy Data:** “A completed project leaves a legacy of products, called artifacts. These artifacts include the source program, specification document, design, and a test plan, as well as data collected during product development. We assume there is a fair amount of quantitative data available for analysis.” [106]
- Lessons-learned:** “Lessons-learned documents are often produced after a large industrial project is completed, whether data is collected or not. A study of these documents often reveals qualitative aspects which can be used to improve future developments. If project personnel are still available, it is possible to interview them to obtain trends in looking at the effects of methods.” [106]

- Literature Search:** "...requires the investigator to analyze the results of papers and other documents that are publicly available. ...a major weakness with a literature search is *selection bias* or the tendency of researchers, authors, and journal editors to publish positive results." [106]
- Local Control:** "refers to the degree to which we can modify the treatment applied to each subject." [106]
- Marco Polo:** "these papers describe experiences and observations related to applying a method, tool, or language in a specific institution or course. Their main impact on the computing education community is exchanging ideas and experiences among teachers." [71]
- (Capability) Maturity Model:** "a methodology used to develop and refine an organization's software development process. The model describes a five-level evolutionary path of increasingly organized and systematically more mature processes." [82]
- Mathematical Modeling:** "One approach to providing understanding comes by offering a model of [an] IT issue in mathematics, and then exploring the model ...sometimes the model is explored ...by simulation, or by expressing the model in code and executing it on case studies. Research of this sort should always be validated by checking that the properties of the model have reasonable fit to properties of the real IT system. This approach to research is often found in subfields that target particular application domains. For example, some researchers have proposed modeling the links in the web as random graphs with particular features; others use queuing networks with particular job distribution as a model for traffic in the internet." [27]
- Mathematical Proof:** "is a demonstration that, assuming certain axioms, some statement is necessarily true. A proof is a logical argument, not an empirical one. That is, one must demonstrate that a proposition is true in all cases before it is considered a theorem of mathematics." [104]
- Melioration:** "The skill of selecting the appropriate amalgam of information and applying it to a solution of problems in situations, which arise at different times and places, thereby meliorating the amalgam." [69]
- Metacognition:** "generally refers to the use of higher order thinking, reasoning, and learning skills during learning, examples of which include goal setting, problem solving, and self-evaluation strategies." [60]
- Meta-analysis:** "A statistical approach for integrating multiple studies ... [with] two steps. First, the experimenters attempt to reconcile the primary experiments – i.e., define a common framework with which to compare different studies ... Next, the data from the primary experiments are transformed or recalculated according to agreed upon definitions." [72]
- Mixed Methods:** "the use of both quantitative and qualitative methods within a single study." [58]
- Monitoring:** "a learning act is a complex process which involves: an awareness of what one is doing, an understanding of where it fits into the established sequence of steps, and an anticipation and planning for what ought to be done next. Furthermore this is all accomplished while one is engaged in the learning act itself." [23]
- Narrative analysis:** is based on the constructivist model that, during an interview, the interviewer and subject interactively reconstruct reality. Narrative analysis reveals the interpretive process, providing a richer understanding of the interview.
- Nominal Scale:** "uses numbers to stand for names or categories. ...The particular number assigned to a class is completely arbitrary." [85]
- Observational method:** "will collect relevant data as a project develops. There is relatively little control over the development process. ...There are four such methods: Project monitoring, Case study, Assertion, and Field study." [106]
- Ordinal Scale:** "uses numbers to order persons or objects on some continuum of, say, low to high." [85]
- Participatory Design:** "(PD) is an approach to the assessment, design, and development of technological and organizational systems that places a premium on the active involvement of workplace practitioners (usually potential or current users of the system) in design and decision-making processes." [15]
- Person-machine Experiments:** "using managers or subjects to model themselves and a computer to model the rest of the organization and environment." [97]
- Pilot Testing:** "a small study carried out prior to a large-scale study in order to try out a technique or procedure." [75]
- Positivist Studies:** "are premised on the existence of a priori fixed relationships within phenomena which are typically investigated with structured instrumentation." [66]
- Proof by Demonstration:** "to build something and then let that artifact stand as an example for a more general class of solutions." [46]
- Proof of Principle:** (also, Proof of Concept) "a claim about the value of a system design (or the design of a part of a system) is validated by building a system based on that design. Typically, the system that is built is not fully featured, but has enough functionality to convince the readers that the design can be effective. The proof-of-concept system is usually measured for performance or usability, to show that the new design is not so bad as to be unworkable." [27]
- Prototype Experiments:** "building 'scale models' of MIS and exercising them within a laboratory setting." [97]
- Qualitative Research:** "The collection of extensive narrative data on many variables over an extended period of time, in a naturalistic setting, in order to gain insights not possible using other types of research." [29]
- Quantitative Research:** "The collection of numerical data in order to explain, predict and/or control phenomena of interest." [29]
- Ratio Scale:** "is an interval scale with a zero point that indicates the absence of the attribute measured. Some familiar examples of ratio scales are length, height, and weight." [85] Note: temperature is not ratio data unless (maybe) you happen to be using the Kelvin scale.
- Reflection:** "can be thought of as the vehicle which transports knowledge between warehouse and learner. As the learner begins a new learning activity, the 'stored' knowledge is

loaded into the reflection vehicle and delivered to the planning dock so that a strategic approach, which matches task and learner variables, can be created.” [23]

**Replication:** “The most important attribute of the scientific method is to be able to replicate the results of an experiment to permit other researchers to reproduce the findings. To ensure that this is so, we must not *confound* two effects. That is, we must make sure that unanticipated variables are not affecting our results.” [106]

**Research:** “The formal, systematic application of the scientific method to the study of problems.” [29]

**Research Approach:** “is defined here as a general approach to studying an area of interest that uses one or more research methods.” [38]

**Research Method:** “is used to denote a specific research strategy, such as survey, experiment, field study, etc.” [38]

**Risk Analysis:** “A systematic method of identifying the assets of a data processing system, the threats to those assets, and the vulnerability of the system to those threats.” [4]

**Scenario Analysis:** “...as it relates to software systems, is the process of analyzing, understanding, and describing system behavior in terms of particular ways the system is expected to be used. The end product of scenario analysis is a document consisting of a set of sufficiently complete, consistent, correct, and validated scenarios.” [42]

**Self-regulated:** “learners utilize three types of strategies to orchestrate their learning: metacognitive, motivational, and behavioral.” ...[strategies include] “setting goals, organizing, self-monitoring, and self-evaluating.” [23]

**Semiotics:** “is the science of signs: graphical, such as pictures; verbal (writing or sounds); or others such as body gestures and clothes. Computer semiotics studies the special nature of computer-based signs and how they function in use.” [3]

**Simulation Experiments:** “computer simulation models of computer-organization problems.” [97]

**Small Group Experiments:** “using managers or other subjects in carefully designed experiments to explore specific human behavior problems in a person-computer system.” [97]

**Static Analysis:** “We can often obtain needed information by looking at the completed product. We analyze the structure of the product to determine characteristics about it. Software complexity and data flow research fit under this model.” [106]

**Stide:** “[is] an immunocomputing process model based on table lookup.” [34]

**Subjective/Argumentative:** “captures creative MIS research based more on opinion and speculation than observation.” [99] *see also Assertion*

**Survey** “involves large numbers of observations; the research uses an experimental design but no controls.” [1]

**Synthesis** (in Bloom’s Taxonomy): “Establishing a whole new creation by combination of ideas from different sources, in a way that formats and molds will be created, and will stand at the basis of the new creation.” [69]

**Synthetic Environment Experiments:** “...most software engineering replications are performed in a smaller artificial setting, which only approximates the environment of the larger projects.” [106]

**Systemic Observation:** “a technique for gathering information about actual use of a system by observing users interacting with it.” [19]

**Taxonomic Methods:** “Taxonomies help to focus research, clarify representation in the literature, define standards, and spot trends or gaps in the research. By categorizing research efforts, taxonomies help provide a measure of order that would go wanting in their absence.” [99]

**Temporal Properties:** “Experiments may be historical (e.g., archaeological) or current (e.g., monitoring a current project). There is certainly less control over the experimental design if the basic data was collected before the experiment began.” [106]

**Theorem Proof:** “captures applicable areas from fields such as Computer Science that otherwise would not be identified.” [99]

**Think Aloud:** “The basic principle of [think aloud] is to ask users to work on typical tasks and to verbalize their task performance and thought process.” [77]

**Trade-off Analysis:** “one of the techniques used in human factors to decide among several design alternatives as a function of several determining criteria or requirements. ...The basic steps in the original technique are the definition of the various alternatives, definition of the requirements or criteria (e.g., cost, reliability, human workload, etc.), assignment of a weighting factor for each criterion, and the computation of the final weight of each design alternative as a function of the criteria.” [68]

**Usability Testing:** “determines whether a system meets a predetermined, quantifiable level of usability for specific types of user carrying out specific tasks.” [75]

**Validation:** “is the process of substantiating that a test measure actually measures what we think it does. This is an important aspect of both quantitative measures (weight, and time are easy, individual question scores on an exam are difficult) and qualitative measures (questions on a questionnaire for example are difficult and time consuming to validate).” [52]

**Validity:** “The degree to which a test measures what it is intended to measure; a test is valid for a particular purpose for a particular group.” [29]

**Visual Proof:** “often involves enactive elements (and usually has verbal support).” “The most basic form of communication is enactive, using gestures and physical actions to convey ideas.” [95]

**Wizard of Oz:** a study in which the functionality of a prototype device is enhanced through a human providing some of the necessary intelligence in a manner masked from the study participants, for example, in [16]