

# Research Directions in Requirements Engineering

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# Research Directions in Requirements Engineering

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## Abstract

*In this paper, we review current requirements engineering (RE) research and identify future research directions suggested by emerging software needs. First, we overview the state of the art in RE research. The research is considered with respect to technologies developed to address specific requirements tasks, such as elicitation, modeling, and analysis. Such a review enables us to identify mature areas of research, as well as areas that warrant further investigation. Next, we review several strategies for performing and extending RE research results, to help delineate the scope of future research directions. Finally, we highlight what we consider to be the “hot” current and future research topics, which aim to address RE needs for emerging systems of the future.*

## 1. Introduction

The success of a software system depends on how well it fits the needs of its users and its environment [127, 130]. *Software requirements* comprise these needs, and *requirements engineering (RE)* is the process by which the requirements are determined. Successful RE involves understanding the needs of users, customers, and other stakeholders; understanding the contexts in which the to-be-developed software will be used; modeling, analyzing, negotiating, and documenting the stakeholders’ requirements; validating that the documented requirements match the negotiated requirements; and managing requirements evolution<sup>1</sup>.

In this paper, we offer our views on the research directions in requirements engineering. The paper builds on Nu-

<sup>1</sup>In addition, there are a number of software-engineering activities that are based on requirements information, such as cost estimation, project planning, and requirements-based derivations of architectures, designs, code, and test cases. Although these activities are “related” to a system’s requirements, they play at most a minor role in determining and agreeing on the system’s requirements; as such, we consider them to be outside the scope of requirements engineering.

seibeh and Easterbrook’s paper [127], hereafter referred to as the “2000 RE Roadmap Paper”, from the Future of Software Engineering track at ICSE 2000 [64]. Whereas the 2000 RE Roadmap Paper focused on current research in requirements engineering, this paper concentrates on research directions and identifies RE challenges posed by emerging and future software needs. We start, in Section 2, with an overview of the inherent difficulties in requirements engineering. In Section 3, we provide a summary of the state of the art of RE knowledge and research, and in Section 4, we enumerate general research strategies for advancing the state of the art. The strategies range from revolutionary research to empirical evaluation to codifying proven solutions. In Section 5, we highlight what we consider to be RE research *hotspots*: the most pressing needs and grand challenges in RE research. Some hotspot topics are natural extensions to existing knowledge and technologies, whereas others arise as RE aspects of predicted software needs. We conclude with strategic recommendations for improving the research infrastructure for RE researchers, thus facilitating the research community’s ability to make better progress on addressing these problems.

## 2. Why Requirements Engineering is Difficult

In general, the research challenges faced by the requirements-engineering community are distinct from those faced by the general software-engineering community, because requirements reside primarily in the problem space whereas other software artifacts reside primarily in the solution space. That is, *requirements* descriptions, ideally, are written entirely in terms of the environment, describing how the environment is to be affected by the proposed system. In contrast, other software artifacts focus on the behavior of the proposed system, and are written in terms of internal software entities and properties. Stated another way, requirements engineering is about defining precisely the *problem* that the software is to solve (i.e., defining *what* the software is to do), whereas other SE activities are

about defining and refining a proposed software *solution*.

Several consequences follow from this distinction that cause requirements engineering to be inherently difficult:

- Requirements analysts start with ill-defined, and often conflicting, ideas of what the proposed system is to do, and must progress towards a single, detailed, technical specification of the system.
- The requirements problem space is less constrained than the software solution space – in fact, it is the requirements definition that helps to delimit the solution space. As such, there are many more options to consider and decisions to make about requirements, such as selecting from collections of proposed requirements, prioritizing requirements, deciding on the system boundaries, negotiating resolutions to conflicts, setting objective acceptance criteria, and so on [172].
- One means of simplifying the problem space is to constrain the environmental conditions under which the system is expected to operate. In such cases, reasoning about requirements involves reasoning about the combined behavior of the proposed system and assumptions made about the environment. Taking into consideration environmental conditions significantly increases the complexity of the problem at hand, since a system's environment may be a combination of hardware devices, physical-world phenomena, human (operator or user) behavior, and other software components.
- Reasoning about the environment includes identifying not only assumptions about the normal behavior of the environment, but also about possible threats or hazards that the environment could pose to the system.
- The resulting requirements artifacts have to be understood and usable by domain experts and other stakeholders, who may not be knowledgeable about computing. Thus, requirements notations and processes must maintain a delicate balance between producing descriptions that are suitable for a non-computing audience and producing technical documents that are precise enough for downstream developers.

Due to all of the above, RE activities, in contrast to other software-engineering activities, may be more iterative, involve many more players who have more varied backgrounds and expertise, require more extensive analyses of options, and call for more complicated verifications of more diverse (e.g., software, hardware, human) components.

### 3. State of the Art of RE Research

In this section, we summarize the state of the art of RE knowledge and research, as a baseline from which to explore future research directions. This section can be viewed

as an update to the 2000 RE Roadmap Paper [127], in that it incorporates advances made in the intervening seven years.

To provide a visual map of RE research, we organize research results in a matrix structure that relates each result to the requirements task that it applies to and the contribution that it makes towards a solution. The research space is roughly decomposed into five types of requirements tasks (elicitation, modeling, requirements analysis, validation and verification, and requirements management) and three categories of solution technologies (notations, methodologies and advice, and techniques). The resulting matrix is shown in Table 2. Not all RE research can be so cleanly classified, but this decomposition is useful for a high-level overview of solution-based research activities; evaluation-based research is discussed separately. Our decomposition is roughly comparable to the top-level decomposition in Zave's proposed scheme for classifying RE research [185].

The rest of this section is organized by requirements task, and thus reviews the contents of the matrix by row. We conclude with a discussion of evaluation-based RE research.

**Elicitation.** *Requirements elicitation* comprises activities that enable the understanding of the goals, objectives, and motives for building a proposed software system. Elicitation also involves identifying the requirements that the resulting system must satisfy in order to achieve these goals. The requirements to be elicited may range from modifications to well-understood problems and systems (e.g., software upgrades), to hazy understandings of new problems being automated, to relatively unconstrained requirements that are open to innovation<sup>2</sup> (e.g., mass-market software). As such, most of the research in elicitation focuses on technologies for improving the precision, accuracy, and variety of the requirements details:

- Techniques for *identifying stakeholders* [152] help to ensure that everyone who may be affected by the software is consulted during elicitation.
- *Analogical techniques*, like metaphors [136] and personas [9, 34], help stakeholders to consider more deeply and be more precise about their requirements.
- *Contextual and personal RE techniques* [33, 160] analyze stakeholders' requirements with respect to a particular context, environment, and perhaps individual user, to help ensure that the eventual system is fit for use in that environment.
- Techniques for *inventing requirements*, like brainstorming and creativity workshops [117], help to identify nonessential requirements that make the final product more appealing.
- *Feedback techniques* use models [65], model animations [84, 115, 170], simulation [164], and storyboards

<sup>2</sup>Innovations are inventions that people are willing to purchase.

**Table 1. Matrix Summarizing the State of the Art of Requirements Engineering**

Requirements Tasks	Requirements Technologies		
	Notations	Methodologies, Strategies, Advice	Techniques, Analyses, Tools
<b>Elicitation</b>	Goals [19, 109, 173] Policies [18] Scenarios [1, 32, 47] Agents [106, 183] Anti-models [157, 166, 174] Nonfunctional requirements [28, 69]	Identifying stakeholders [152] Metaphors [133, 136] Persona [9, 34] Contextual requirements [33, 160] Inventing requirements [117]	Animation [84, 115, 170] Simulation [164] Invariant generation [93]
<b>Modeling</b>	Object models [89] Behavioral models [92, 167] Domain descriptions [11] Property languages [14, 50, 105] Notation Semantics [59, 120, 125, 163]	RE reference model [75, 77, 131] Model elaboration [169] Viewpoints [128, 155] Patterns [49, 54, 90, 99, 171] Modeling facilitators [6, 31, 72, 97, 129] Formalization heuristics [18, 67] Methodologies [15]	Model merging [147, 165] Model synthesis [3, 39, 107, 168, 182] Model composition [80]
<b>Requirements Analysis</b>		Negotiation [87] Aligning requirements with COTS [5, 144] Conflict management [143]	Linguistic analysis [16, 27, 176] Ontologies [95] Checklists [177] Consistency checking [58, 83, 123] Inspections [60, 132] Conflict analysis [25, 79] Obstacle analysis [114, 175] Risk management [62] Impact analysis [101] Causal order analysis [12] Prioritization [122] Variability analysis [74, 108, 110] Requirements selection [139, 159]
<b>Validation &amp; Verification</b>	Model formalisms [22, 51]		Simulation [164] Animation [84, 115, 170] Invariant generation [93] Model checking [26, 55, 158] Model satisfiability [89]
<b>Requirements Management</b>	Variability modeling [21, 38, 140, 150]	Scenario management [2] Feature management [179] Global RE [44]	Traceability [30, 81, 146, 151] Stability analysis [23]

to elicit positive and negative feedback on early representations of the proposed system.

Models can be used during elicitation to help catalyze discussion and to explore and learn about the stakeholders' needs. Such exploratory models, like use cases, scenarios, enterprise models, and some policy [18] and goal models [19], tend to be informal and intuitive, to facilitate early feedback from stakeholders. They tend also to be inexpensive to create and maintain, so that specifiers can keep them up-to-date as the requirements evolve.

**Modeling.** In *requirements modeling*, a project's requirements or specification is expressed in terms of one or more models. In contrast to models developed during elicitation, late-phase requirements models tend to be more precise, complete, and unambiguous. The process of creating precise models helps to evoke details that were missed in the initial elicitation. The resulting (more complete) models can be used to communicate the requirements to downstream developers.

Modeling notations help to raise the level of abstraction in requirements descriptions by providing a vocabulary and structural rules that more closely match – better than natural language does – the entities, relationships, behavior, and constraints of the problem being modeled. Each modeling notation is designed to elicit or record specific details about the requirements, such as what data the software is to maintain, functions on the data, responses to inputs, or properties about data or behavior.

Scenario-based models [1, 3, 39, 47, 165, 168, 169, 182] have been the focus of much recent research – partly because scenarios are easiest for practitioners and nontechnical stakeholders to use, but perhaps also because scenarios are naturally incomplete and thus lend themselves to a plethora of research problems. In addition, there is considerable research on techniques for creating, combining, and manipulating models:

- *Modeling strategies* provide guidelines for structuring models. For example, *RE reference models* [75, 77, 131] decompose requirements-related descriptions into the stakeholders' *requirements*, the *specification* of the proposed system, and assumptions made about the system's *environment*. In addition, they establish correctness criteria for verifying that the specified system will meet the requirements. In contrast, the *view-points* approach [128, 155] retains each stakeholder's requirements in separate models, and the synthesis of a consistent global model that captures all of the stakeholders' concerns is delayed until conflicts can be resolved knowledgeably.
- *Patterns* encode generic solutions to common modeling problems [90, 99, 171], assertion expressions [54],

and natural-language requirements statements [49]. The RE community is also working on tools [31, 97, 129] to help specifiers apply these patterns.

- *Model transformations* combine or manipulate existing models to derive new models. For example, *model synthesis* [3, 39, 107, 168, 182] and *model composition* techniques [80] integrate complementary submodels into a composite model. In contrast, *model merging* techniques [147, 165] unify different views of the same problem.

Several of the above-mentioned projects directly address challenges raised in the 2000 RE Roadmap Paper. For example, heuristics for formalizing natural-language policies [18] and goal models [67] help to bridge the gap between informal and formal requirements. This gap is also narrowed by techniques for inferring abstractions [72] and preliminary models [6] from natural-language requirements, by tools that map constrained natural-language expressions to formal representations [31, 97, 129], by research on formalizing the semantics of informal or semi-formal modeling notations [59, 71, 120, 163]. In addition, significant advances have been made in the modeling and analysis of nonfunctional requirements [28] and in establishing objective fit criteria for how well an eventual system must achieve various nonfunctional properties [69]. On the other hand, there has been little progress on special-purpose notations for modeling environment descriptions and assumptions [11]. Instead, existing notations like functions [131], operational specifications (e.g., Z, Alloy [89]), and constraint languages continue to be used.

**Requirements Analysis.** Most of the research in *requirements analysis* focuses on new or improved techniques for evaluating the quality of recorded requirements. Some analyses look for well-formedness errors in requirements, where an "error" can be ambiguity [16, 61, 95, 149, 176], inconsistency [24, 58, 123], or incompleteness. Other analyses look for anomalies, such as unknown interactions among requirements [25, 79, 143], possible obstacles to requirements satisfaction [114, 175], or missing assumptions [12]. Both types of analyses reveal misunderstandings or questions about the requirements that usually call for further elicitation. Requirements analysis also includes techniques, such as risk analysis [62] and impact analysis [101], that help specifiers to better understand the requirements, their interrelationships, and their potential consequences, so that specifiers can make more-informed decisions. As other examples, prioritization, visualization, and analysis techniques help a manager to select an optimal combination of requirements to be implemented [74, 110, 139, 122, 159], or to identify acceptable off-the-shelf solutions [104, 144].

**Validation and Verification.** *Requirements validation* ensures that models and documentation accurately express the stakeholders' needs. Unlike the above analyses that check a specification against objective well-formedness criteria, validation is typically a subjective evaluation of the specification with respect to informally described or undocumented requirements. As such, validation usually requires stakeholders to be directly involved in reviewing the requirements artifacts [145]. Research in this area focuses on improving the information provided to the stakeholder for feedback, including animations [84, 115, 170], simulations [164], and derived invariants [93].

In cases where a formal description of the stakeholders' requirements exists, obtained perhaps by validation, *verification* techniques can be used to prove that the software specification meets these requirements. Such proofs often take the form of checking that a specification model satisfies some constraint. For example, *model checking* [26, 55, 158] checks behavioral models against temporal-logic properties about execution traces; and *model satisfiability* [89] checks that there exist valid instantiations of constrained object models, and that operations on object models preserve invariants.

The notations listed in the *Validation & Verification* row of Table 2 represent formalisms that enable or ease verification. In contrast to specification notations, these notations' primary purpose is to facilitate automated verification rather than to communicate or document requirements. Verification models, expressed in these notations, are simplifications and abstractions of a specification to be verified [22, 51, 89].

**Requirements management.** *Requirements management* is an umbrella activity that comprises a number of tasks related to the management of requirements, including the evolution of requirements over time and across product families. Of particular interest are tools and techniques to ease, and partially automate, the task of identifying and documenting traceability links among requirements artifacts and between requirements and downstream artifacts [30, 81, 118, 146, 151]. Also included are analyses that determine the maturity and stability of elicited requirements, so that the requirements most likely to change can be isolated [23]. Lastly, the basic management of requirements has become a challenge and has inspired research on techniques to organize large numbers of requirements [2] that are globally distributed [44], and that are at different phases in development in different product variants [179].

**Evaluation-Based Research.** The above discussion is an overview of solution-based RE research, which emphasizes technological advances that make progress towards solving RE problems; such research is often accompanied by

proofs-of-concepts or pilot studies that show the potential of the proposed ideas. Orthogonal to this work is *evaluation-based research*, whose mission is to assess the state of the practice and evaluate proposed advances to the state of the art. Approximately 10% to 15% of RE research papers report on evaluation-based research, in the form of reports on the state of the practice [46], case studies that evaluate how well research ideas work when applied to industrial-strength problems<sup>3</sup> [87, 112, 116, 121, 181], and field studies that evaluate research ideas in industrial settings [40, 42, 66]. Several recent research projects evaluate how well requirements technologies apply to, or can be adapted to, domain-specific problems, such as security [174], semantic webs [52], and user interfaces [17]. Additionally, there have been a few comparative studies that compare the effectiveness of competing elicitation techniques [48, 56], specification notations [10], and inspection techniques [135]. Finally, there have also been some post-mortem analyses on how requirements evolved in real-world systems [8, 113].

## 4. Research Strategies

In this section, we discuss ways of advancing the state of the art of RE research. We review several major strategies for conducting research, and look at how each have or might be applied to requirements-related research. The strategies range from inventing new disruptive ideas and technologies, to improving on current research, to adapting previous results to a new context, to evaluating or comparing technologies. Each strategy attempts to achieve a slightly different research objective, but all contribute in some way to advancing the state of the art, either by adding new knowledge or by improving the maturity of previous work.

Our collection of research strategies is synthesized from a number of different sources, including Shaw's overview of criteria for good research in software engineering [154], Redwine and Riddle's review of software technology maturation [138], Basili's review of research paradigms [13], and the combined experience of both authors. Table 2 introduces and briefly defines the eight research strategies that we discuss below. The strategies are listed in order of increasing maturity of the research results.

**Paradigm Shift.** A *paradigm shift* is a revolutionary solution that introduces radically new ideas or technologies to tackle a new or existing problem. Paradigm shifts are rare and are usually unplanned; but when they occur, they can have tremendous impact on a field. A paradigm shift is triggered by an important problem that researchers can

<sup>3</sup>We use the term "industrial-strength" problems/projects to refer project data that have characteristics of industrial data, such as size, complexity, and/or domain-specific properties.

**Table 2. Enumeration of research strategies**

Research Strategy	Definition
<b>Paradigm Shift:</b>	Dramatically change the way of thinking, resulting in a revolution in knowledge or technology.
<b>Leverage other disciplines:</b>	Leverage and recast principles, practices, processes, or techniques from another discipline.
<b>Leverage new technology:</b>	Make advances by leveraging new tools or technology.
<b>Evolutionary:</b>	Make progressive improvements to existing research solutions and techniques.
<b>Domain-specific:</b>	Develop a new solution or technique that applies narrowly to a specific problem domain.
<b>Generalization:</b>	Generalize an existing solution or technique, so that it applies to a broader class of problems or data.
<b>Engineering:</b>	Develop processes or strategies that make it easier or cheaper to apply research solutions in practice.
<b>Evaluation:</b>	Evaluate existing research solutions – with respect to specified metrics, real or realistic problems, current practices, or related research results.

no longer make progress on by extending or adapting existing technologies. The shift starts with some innovative change in the way that a particular problem is considered. The change leads to disruptive innovations, which usually must mature before their benefits are recognized and appreciated enough to motivate rapid and widespread adoption.

Typically, there are two means by which a paradigm shift occurs: push and pull. A paradigm shift is *pushed* onto a community when new technology serendipitously makes major advances towards solving a problem for which it was not originally intended. A classic example of such a shift is the World Wide Web, which has significantly changed the way that society communicates and the way that services are delivered to consumers. A paradigm shift that is currently underway is the shift toward global software development and, by extension, global requirements engineering; we discuss this topic further in Section 5.6.

Alternatively, a paradigm shift can be *pulled* when there is a real or a perceived crisis that cannot be solved by improving current ideas and techniques [102]. For example, object-based design conventions were invented in response to serious concerns about how to structure programs and data in a way that promoted modularity according to application- and data-driven abstractions. As the design conventions gained popularity, they evolved into object-oriented programming methodologies, were codified in new design methods, and were eventually supported by new programming language constructs.

**Leverage other disciplines.** An RE researcher can leverage another discipline by identifying the analogous relationships between the two disciplines and then recasting promising knowledge, philosophies, principles, or practices

from the other discipline into solutions that are appropriate for requirements problems. For example, software engineering, as a discipline, emerged when researchers and practitioners attempted to manage the “software crisis” by borrowing and adapting from the engineering profession several ideas about design principles, development processes, and discipline. As another example, the concept of genetic algorithms leverages ideas from biology, in that the algorithms “evolve” by using feedback from previous computations to improve future computations. Sutcliffe et al. [124] use genetic algorithms to improve the efficiency of searching for an optimal requirements decision by optimizing a fitness function that reflects reliability requirements. As a third example, Sutcliffe and Maiden’s work [161] in establishing a domain theory for RE draws heavily from cognitive science and analogical reasoning.

**Leverage technology.** Technological advances in computing and related fields can be combined and adapted to apply to problems in requirements engineering. In general, artificial intelligence, library science, information science, cognitive psychology, linguistics, statistics, and mathematics are all fertile areas for ideas and techniques that are suitable for such adaptation. For example, Ambriola and Gervasi [6], and separately Overmeyer et al. [129], use natural-language processing techniques to parse textual requirements descriptions and to generate corresponding semi-formal models, such as data-flow diagrams and communication diagrams. They and other researchers [6, 16, 61, 149, 176] use linguistic-analysis techniques to detect possible ambiguities and unintended inconsistencies in textual or use-case requirements. Hayes et al. [81] and Cleland-Huang et al. [29] use information-retrieval techniques to automati-

cally retrieve traceability links among requirements.

**Evolutionary research.** The antithesis of a paradigm shift is evolutionary research, in which the state of the art advances via incremental improvements to existing technologies. Although emerging software needs may pose new research challenges that the RE community will be called on to address, most software developed in the near future will resemble the types of systems being developed today. As such, the software community will continue to benefit from improvements to current requirements technologies (as overviewed in Section 3), which were created in response to the problems that today's practitioners face.

In many ways, evolutionary research is about moving research technologies down the research-strategy ladder listed in Table 2. Existing notations and techniques can be extended, adapted, or generalized to address a broader class of problems. Current technologies can be supported by new methodologies, patterns, strategies, and tools that ease their use and help to promote their adoption by practitioners. Empirical research can determine the problems and contexts for which a technology is most effective, and can identify aspects that could be further improved.

**Domain-specific.** A researcher can sometimes make better progress by narrowing the scope of a requirements problem and studying it in the context of a particular application domain. For example, there is a paradigm shift towards more domain-specific specification languages [65] that provide native facilities for describing important entities and behaviors in that domain and provide macros for eliding recurrent requirements details. Along these lines, the International Telecommunication Union (ITU) has standardized a number of specification, design, and testing languages; design methodologies; and interface specifications – all of which support software aspects of telecommunication systems.

**Generalization.** Successful domain-specific or organization-specific techniques can sometimes be generalized to be more broadly applicable. For example, many of the ideas in telecommunications notations, like Message Sequence Charts and the Specification and Description Language, have been incorporated into the more general Unified Modeling Language 2.0. As another example, techniques for avoiding, detecting, and resolving feature interactions, which were originally developed in the context of telephony features [80, 184], are now being studied and applied in other domains, such as Web services [180].

**Engineering.** A surprising number of research problems arise in the course of trying to apply requirements technologies in practice. Engineering as a research strategy

looks at how to simplify and codify RE knowledge and techniques so that they can be readily adopted by practitioners and taught in classrooms. For example, visual formalisms [50, 53, 78, 92] ease the task of creating and reviewing precise specifications. Patterns not only help specifiers to create models [98, 99, 171] and express constraints [54], via instantiation and adaptation, but they also offer some level of uniformity and reusability of such descriptions. Heuristics and strategies offer advice on how to use particular elicitation [7], modeling [18, 67], or verification [94] technologies. Methodologies and processes provide guidance on how to integrate RE technologies into a coherent series of steps that progress from an initial idea to a final specification document [137, 141]. One of the best known engineering-style research projects was Parnas et al.'s case study that applied state-of-the-art software-engineering practices to (re)develop the engineering artifacts and code for the U.S. A-7 naval aircraft. This work led to research results in tabular specifications [92], hierarchical module structures, abstract interfaces, and new inspection strategies [132].

**Evaluation.** Proposed RE technologies become theories, solutions, or practices through evaluation-based research that demonstrate effectiveness. Evaluation techniques include experience, collection and analysis of data, field studies, case studies, controlled experiments, and analytical reasoning. Evaluation criteria range from qualitative or statistical metrics, to effectiveness in solving real or realistic problems, to comparisons with competing technologies. A mature RE technology should be evaluated on real-world applications or in an industrial setting, to assess its scalability, practicality, and ease of use [66, 87, 112, 116, 121, 181]. In contrast, comparative studies evaluate the relative strengths and weaknesses of competing solutions to a problem. Notable comparative studies have investigated the criteria for choosing a specification language [10] and the effectiveness of methods for inspecting requirements documents [135].

Evaluation-based research need not be a massive undertaking. A case-study may be based on a single study involving an industrial-strength project, on replicated studies of the same project, on studies of multiple projects, or on a longitudinal study that spans several phases of a project. Even the development of new assessment criteria, such as appropriate benchmarks, are valuable research contributions.

## 5. RE Research Hotspots

As evidenced by the previous sections, the field of RE research is rich, and the scope of possible research directions is quite large. In addition, new RE research challenges may arise from emerging trends in software systems and predictions about future software needs. Current trends



and expressed needs include increasing scale of software systems, tighter integration between software and its environment, greater autonomy of software to adapt to its environment, and increasing globalization of software development. These trends reflect changes in stakeholders' needs, and as such they directly affect RE processes and practices. In some cases, current technologies can accommodate the new trends in requirements. In other cases, the trends pose new research challenges in requirements engineering, or raise the priorities of longstanding research problems.

In this section, we call attention to nine RE research *hotspots* whose solutions are likely to have the greatest impact on software-engineering research and practice. Our list of hotspots is not meant to be exhaustive. Rather, it is intended to highlight some of the more pressing needs and grand challenges in RE research. Of the nine hotspots discussed below, six arise from future software needs, due to predicted increases in scale, security, tolerance, dependencies between software and its environment, self-management, and globalization. The other three hotspots focus on extending and maturing existing technologies to improve RE methodologies and requirements reuse and on increasing the volume of evaluation-based research.

### 5.1. Scale

Software systems are growing in size. Moreover, the "scale" of large-scale systems no longer refers simply to significant size, as in lines of code. Scale factors also include complexity, degree of heterogeneity, number of sensors, and number of decentralized decision-making nodes. Yet another scale factor is variability, as software systems need to accommodate increasingly larger sets of requirements that vary with respect to changes in the software's environment. An example class of systems that exhibit many of these new scale factors are the ultra-large-scale (ULS) systems [126] proposed for next-generation military command and control systems. Other potential ULS systems include future intelligent transportation-management systems, critical infrastructure protection systems (e.g., systems managing power grids, bridges, telecommunication systems), integrated health-care systems, and disaster-response systems.

Modeling, abstraction, and analysis techniques that scale well are critical in designing ULSs. Current modeling paradigms and analysis techniques cannot effectively manage the scale, complexity, variability, and uncertainty that are predicted for these systems. Requirements will come from many different stakeholders, involve multiple disciplines (e.g., sensors, scientific computation, artificial intelligence), and be presented at varying levels of abstraction. Thus, new abstractions, innovative decomposition strategies, standardized composition operators, and increased au-

tomation of RE tasks are all needed to cope with the complexity. In addition, better techniques are needed to merge potentially vastly different types of requirements into a single coherent story. Detecting and resolving feature interactions and conflicts on such a large scale will pose a grand challenge. Taken together, these problems call for new paradigms for thinking about, modeling, analyzing, and managing requirements.

### 5.2. Security

As computing systems become ever more pervasive and mobile, and as they automate and manage more consumer-critical processes and data, they increasingly become the targets of security attacks. Moreover, attacks originate from both outside the system and within (e.g., a human operator), are intentional, and are constantly changing. For these reasons, we believe that security poses challenges to RE that exceed those posed by other nonfunctional requirements, and so we elevate it to be a research hotspot.

There has been substantial work on how to improve software security, in the form of solutions and strategies that (1) avoid vulnerabilities, (2) protect systems and information, and (3) defend against or recover from attacks. However, most of these solutions are design or implementation results, and are threat-specific. Thus, the associated RE tasks are to identify and document potential security threats. Specifically, the specifier identifies assets, identifies vulnerabilities in the context of potential threats, and specifies countermeasures to protect against these threats. Example efforts include anti-models [119, 157, 166, 174], trust assumptions [76], and threat modeling [88, 162].

Although strategic, the threat-based approach to security requirements engineering is reactive and focuses on low-level security requirements; there is no notion of a general security policy. An alternative approach would take a top-down view of security requirements, and base requirements on organizational structures, such as lines of authority, "separation of duties, delegation, roles, groups," access policies, and so on [36]. Work on notations and methodologies for structuring, modeling, and reasoning about high-level security policies is just beginning [35, 70, 82].

To further add to the challenge, there is no consensus on the degree to which security requirements should be realized at the requirements level. Should specifiers go so far as to select and employ appropriate protections for identified threats, in the manner that user interfaces and timing deadlines are woven into behavioral specifications? Or should detailed security measures be optimized at design time along with other competing nonfunctional requirements? These are open questions for the RE and security communities to resolve.

### 5.3. Tolerance

Software is increasingly used to automate critical applications and services, such as transportation vehicles and systems, financial decisions and transactions, medical care, military command and control, and so on; in which security and assurance requirements are paramount. However, given the complexity of such systems, with respect to size, decentralized decision-making, and variability, the SE and RE communities may need to soften their views and expectations for security and correctness. Shaw [153] discusses the need to accept “sufficient correctness” for complex systems, instead of striving for absolute correctness that may lead to brittle systems.

**Sufficient Correctness:** *The degree to which a system must be dependable in order to serve the purpose its user intends, and to do so well enough to satisfy the current needs and expectations of those users [153].*

When operating in an uncertain and dynamically changing environment, brittle systems tend to fail at the first encounter of adverse conditions. To avoid this problem, requirements elicitation should focus on requirements for acceptable behavior and on what it means for a system to be “healthy” [153]. One approach to relaxing the precision of correctness criteria is to specify (fault) tolerance requirements, which extend the ranges of acceptable behavior. For example, Wassyyng et al. [178] have made some preliminary progress on specifying timing requirements in a way that is precise and yet captures allowable tolerances. Alternative approaches include focusing on negative requirements, which represent “unhealthy” conditions or behaviors that the system must avoid, and on requirements for diagnostic and recovery mechanisms.

### 5.4. Increased Reliance on the Environment

The increase in scale is partly due to the rise of systems of systems, consisting of software, hardware, and people, all of which may be loosely or tightly coupled together. For example, *cyber-physical systems* (CPSs) are a new generation of engineered systems in which computing and communication are tightly coupled with the monitoring and control of entities in the physical world [37]. Example cyber-physical systems include intelligent transportation and vehicle systems; automated manufacturing; critical infrastructure monitoring; disaster response; optimization of energy consumption; smart wearable attire [68] for health care, personal safety, and medical needs; and efficient agriculture [37].

Integrated systems pose particularly thorny requirements problems because of their coupling with and dependence on the physical environment. Such systems recast old RE

problems of determining the software system’s boundary into more complicated problems of assigning responsibilities: to the software system under consideration, to peer software systems, to hardware interface devices (which are increasingly programmable), and to human operators and users [106]. Moreover, the environment or context in which a software system will run is often the least understood and most uncertain aspect of a proposed system; and RE technologies and tools for reasoning about the integration of physical environment, human behavior, interface devices, and software system are among the least mature.

To reason about an integrated system, it becomes necessary to formalize the properties of the environments with which the software will interoperate. Jackson [91] explores a number of challenges in modeling and reasoning about a software system’s environment, including working with formalizations that are necessarily “imperfect...[discrete approximations] of continuous phenomena”, devising piecewise formalizations of the environment to support different proofs about the software, and ensuring that the environment is in a “compatible state” when the system initializes [91]. Towards this end, better abstractions are needed to model the behaviors of physical and human entities and their interfaces with computing elements. New domain-specific languages may be needed to express these domain abstractions and knowledge; and new languages would call for corresponding simulation, verification, and visualization techniques, to validate the modeled environment.

Most importantly, there need to be better techniques for integrating models of the environment, interface devices, and software components. Computing devices tend to be modeled using discrete mathematics, such as logics and automata; physical devices tend to be modeled using continuous mathematics, such as differential equations; and human-behavior modeling is an open problem, with researchers using a combination of goals, agents, relationship models, and performance moderator functions [156]. Researchers in the verification community are making progress on the modeling, simulation, and reasoning of hybrid models [4], but their work does not accommodate human-behavior models, and the scalability of techniques remains an elusive goal.

### 5.5. Self-Management

The difficulties of requirements engineering are aggravated by the desire to create software systems that accommodate at run-time varying, uncertain, incomplete, or evolving requirements. For example, there is growing interest in *self-managing systems*, in which the software system is aware of its context and is able to react and adapt to changes in either its environment or its requirements [100] – such as a mobile device, whose available services vary with the user’s location and with the local service provider(s).

Examples of such systems include *self-healing systems* that are able to recover dynamically from system failure, faults, errors, or security breaches; and *self-optimizing systems* that are able to optimize their performance dynamically with respect to changing operational profiles.

Self-management capabilities are essential in software systems that, once deployed, cannot be accessed physically or electronically. For example, a cyber-physical system (CPS) may have large numbers of physically distributed sensors that are placed in difficult-to-reach locations, such as power transformers, nuclear reactor cores, and hazardous or toxic sites. Moreover, these sensors are increasingly programmable. If developers are not able to access remote elements to perform software updates, then the elements will need to update and correct themselves.

In the simplest case, a self-managing system adapts its behavior at run-time by replacing the running system with a new target behavior selected from among a set of predefined behaviors. These systems require different perspectives on the types of requirements information that should be considered and documented – in contrast to traditional approaches, which typically focus on static goals or functionality. The RE research problems posed by such a system include

- Identifying and specifying thresholds for when the system should adapt
- Specifying variable sets of requirements
- Matching requirements alternatives to run-time needs
- Identifying correctness criteria for adaptive systems
- Verifying models of adaptive systems and their sets of possible behaviors
- Monitoring the system and environment, against the current requirements

There has been some preliminary work on specifying and verifying adaptive software [103, 186, 187] and on run-time monitoring of requirements conformance [63, 142, 148]. In addition, much of the work on *personalized* [160] and *customized* [111] software – at least with respect to eliciting, modeling, and reasoning about requirements variations – can also be applied to adaptive systems.

However, there is an assumption with customized and self-managed systems that it is possible to predict and pre-define the requirements for a complete set of target behaviors. Such predictions may not be possible, if the system is to recover dynamically from unexpected errors or attacks, or adapt at run-time to new environmental conditions or to new requirements that were not anticipated during development. In this case, what is needed is a *self-evolving* system that is able, at run time, to satisfy new requirements and behaviors. Thus, the requirements analyst needs to specify how the system's requirements can evolve dynamically;

specify abstract adaptation thresholds that allow for uncertainty and unanticipated environmental conditions; and verify the adaptation decision-making capabilities of the resulting system. Unfortunately, none of the existing modeling and verification techniques address the challenges posed by this degree of evolution, uncertainty, and incomplete information.

One research strategy would be to investigate whether ideas from other disciplines, such as biology, could be leveraged. Given that natural organisms are inherently able to respond to adverse and unexpected conditions, biological entities and systems may be suitable metaphors for dynamically adaptive software. *Biomimetics* comprises those techniques that attempt to imitate or simulate the behavior of natural organisms. For example, work at Michigan State University is exploring how digital evolution techniques can be extended to simulate a biological evolution process that discovers new unanticipated behavior, and thus new requirements, for the adaptive systems [73, 96].

## 5.6. Globalization

*Global software development* is an emerging paradigm shift towards globally distributed development teams [86]. The shift is motivated by the desire to exploit a 24-hour work day, capitalize on global resource pools, decrease costs, and be geographically closer to the end-consumer [44]. The downside is increased risk of communication gaps. For example, elicitation and early modeling are collaborative activities that require the construction of a shared mental model of the problem and requirements. However, there is an explicit disconnect between this need for collaboration and the distance imposed by global development.

Globalization poses two main challenges to the RE research community. First, new or extended RE techniques are needed to support outsourcing of downstream development tasks, such as design, coding, and testing. Distance aggravates the gap between the requirements and development teams, particularly if the teams are from different organizations, have different cultures, or have different work environments. In particular, because geographic distance reduces team communication [85], ill-defined requirements are at risk of ultimately being misinterpreted, resulting in a system that does not meet the stakeholders' needs. As a preliminary effort to narrow communication gaps, Bhat et al. [44] have proposed a framework based on a people-process-technology paradigm that describes best practices for negotiating goals, culture, processes, and responsibilities across a global organization.

The second challenge is to enable effective distributed RE. Future requirements activities will be globally distributed, since requirements analysts will likely be working

with geographically distributed stakeholders and distributed development teams may work with in-house customers. As such, practitioners need techniques to facilitate and manage distributed requirements elicitation, distributed modeling, distributed requirements negotiation, and the management of distributed teams – not just geographically distributed, but distributed in terms of time zone, culture, and language. Damian and her group are interested in distributed requirements negotiation, and have investigated how best to use and combine different media technology to facilitate negotiations and quality agreements [42, 43]. Sinha et al. have developed an Eclipse-based tool for distributed requirements engineering collaboration [44].

### 5.7. Methodologies, Patterns, and Tools

The transfer of RE technologies from research into practice would benefit from better advice on how to apply the technologies more systematically. The goals of this type of engineering-style research are to improve the productivity of the requirements analyst and to improve the quality of the resulting requirements artifacts. For example, just as patterns [54] help to ease the creation of logic expressions, research into idioms and patterns for other modeling problems and notations [98, 99, 171] would improve the productivity of modelers.

Similarly, modeling conventions, methodologies, and strategies all help to simplify RE techniques so that the techniques can be used successfully by typical practitioners. Because patterns and strategies are, or suggest, partial solutions, they help also to impose some level of uniformity and predictability in the resulting requirements descriptions.

Engineering-style research is also needed to investigate how to integrate requirements technologies into a coherent requirements process. Most research projects focus on a single RE problem, such as elicitation or traceability. As a result, the state of the art in RE research is a collection of technologies that have been researched and evaluated in isolation, with little knowledge of how to combine techniques effectively. For example, despite the significant advances that have been made in requirements modeling and notations, there has been little work on how to interconnect various types of requirements models. Well-defined approaches to interrelating requirements goals, scenarios, data, functions, state-based behavior, and constraints are needed to address this fundamental problem. Broy and his group have made some progress on this problem, in the form of a modeling theory that incorporates many of the above-mentioned modeling elements [20]. As an example of synergy among RE technologies, Ebert [57] shows via an analysis of several industrial-development projects that four product-management techniques, used for composing teams, negotiating requirements, planning long-term prod-

uct and feature releases, and tracking a product's status, are most effective at reducing scheduling delays when the techniques are used together. Further research is needed on how to integrate RE technologies, so that practitioners know how to apply individual technologies effectively and synergistically.

### 5.8. Requirements Reuse

Another approach to making RE tasks more prescriptive and systematic would be to facilitate the reuse of existing requirements artifacts. The most strategic form of requirements reuse is *product lining*, where related products are treated as a product family, and their co-development is planned from the beginning. The family's common requirements are collected in reusable templates that can be instantiated and adapted to derive the requirements for an individual product. A key RE challenge for product-line development includes strategic and effective techniques for analyzing domains; identifying opportunities for product lining; and identifying the scope, commonalities, and variabilities of a product line. A second challenge relates to how requirements for product lines are documented. Feature models [38, 134] are commonly used to model a product-line core, but they quickly proliferate when used to model product-line instantiations. A promising but untested solution to this challenge is multi-level feature trees [140].

Expression and modeling patterns, discussed in the previous section, are also a form of reuse, in that they codify reusable modeling structures. Problem frames [90] can be considered abstract patterns of context diagrams for common classes of software problems, and thus are also reusable. In addition, it may be possible to identify larger units of reusable requirements for particular domains or particular types of applications. The automotive industry has expressed interest in using such "generic, reusable requirements" in developing complex automotive systems.

A reusable requirement should be accompanied by standard pattern fields, such as context, problem addressed, consequences, properties, and so on. However, this is usually not enough information to facilitate effective use of the pattern or reusable artifact. Adapting an instantiated pattern so that it adequately fits the desired context is still a bit of an art. Pattern use would be easier and more successful if practitioners had better guidance and examples of how to apply and adapt individual patterns.

### 5.9. Effectiveness of RE Technologies

Lastly, the ultimate impact of RE research depends on how relevant the results are to industry's short- and long-term needs. So far, there has been surprisingly little evaluation as to how well RE research results address indus-

trial problems. As mentioned in Section 3, most empirical RE research takes the form of proofs-of-concept or pilot studies, both of which qualitatively evaluate how well a proposed solution or technique applies to a single concrete problem. Such studies tend to be aimed at research audiences, and are intended to convince readers that the RE technologies under evaluation advance the state of the art. However, given that most studies report success, how is a practitioner to determine when a study reports a significant enough advance to warrant changes to the state of the practice, and how is a practitioner to select from among competing technologies?

Practitioners need hard evidence that a new technology is cost-effective, in order to justify the overhead, in training and in process documentation, of changing their development processes. In particular, practitioners would benefit greatly from empirical studies that assess the costs and benefits of using proposed technologies, assess the scope of problems to which research results can feasibly be applied, and compare the effectiveness of competing technologies. There have been a few studies along these lines. Damian et al. have conducted a series of surveys that evaluates the impact of requirements-related activities on productivity, risk management, and the quality of both requirements and downstream artifacts [40, 41, 45]. The Comparative Evaluation in Requirements Engineering (CERE) workshops investigate how to facilitate comparative studies, such as the development of suitable benchmarks. The Economics-Driven Software Engineering Research (EDSER) workshops investigate how to improve practitioners' abilities to make economics-based SE decisions, such as whether or not to adopt new technologies. Such empirical research that evaluates requirements technologies in the context of industrial settings and practices would help to accelerate the transfer of research results into RE practice.

## 6. Recommendations and Conclusions

In this paper, we have described a number of exciting and challenging research directions in requirements engineering. Some of these directions are natural extensions of work already being performed by RE researchers, whereas others are major discontinuities due to fundamental changes in computing needs. All of the problems described above will require substantial effort in order to make progress towards effective solutions. To help alleviate this effort, we offer some recommendations of short- and long-term actions that the RE community could take, to position itself to make more rapid progress on these research problems.

There are five recommendations that the RE community could take immediate action on, to start improving the maturity of current requirements technologies:

- Researchers should work with practitioners. Such part-

nerships can help to ensure that researchers have a through understanding of the real problems that practitioners face.

- RE researchers should work with other SE researchers and practitioners, to establish stronger links between their respective artifacts. If the transition between RE tasks and other development tasks were more seamless, management would view RE efforts more positively, because the resulting requirements knowledge and artifacts would make more concrete progress towards achieving downstream milestones.
- RE researchers should not neglect evaluation and empirical research. For practitioners to consider adopting a given research technique, they must know how the technique compares with similar techniques. Also, practitioners and their managers need to see that the technique can be applied to problems relevant to their organization, from both domain and scale perspectives.
- Industrial organizations should provide (sanitized) industrial-strength project data to researchers. It is especially critical that industry provide realistic data for ultra-large scale or cyber-physical systems to ensure that researchers tackle problems that are representative of those faced by practitioners. Researchers can use this data to guide the development and validation of their new techniques, thereby yielding more relevant and useful research results that explicitly address industrial needs.
- RE researchers and practitioners, together, should establish repositories of RE artifacts. Such repositories can serve as a resource for practitioners and educators to share best practices and exemplar artifacts. Repositories can also store requirements patterns for potential reuse, case studies that evaluate individual or composite RE techniques, benchmark data for evaluating competing technologies, and tools that support specific RE techniques.

The above actions would help the RE research community to make immediate progress on improving existing knowledge and techniques. In addition, there are some longer-term actions that would help to improve the community's research infrastructure and its ability to confront the challenges posed by emerging systems:

- The RE community needs to be proactive in identifying the RE research problems that arise from new computing challenges. New challenges reflect changing stakeholders' needs. As such, RE researchers should be involved in the initial investigations of any new computing challenge, to help tease out the essential goals and to assess their impact on RE tasks.

- Researchers need to think beyond current RE and SE knowledge and capabilities, in order to make significant headway in addressing the challenges posed by emerging systems. They need to be willing to search for new solutions that may lead to paradigm shifts in RE practices, at the risk of possible failure. One strategy is for researchers to seek out collaborators from other disciplines to leverage successful techniques that could be used to address analogous challenges faced by cyber systems.
- RE academics need to educate the next generation of developers on RE problems and technologies. Students need curricula that combine the study of computing with the study of specialized application domains. They also need computing courses that teach them how to make design decisions that achieve requirements (e.g., modularity vs. performance requirements) in the context of the software's operating environment.

In conclusion, the RE research community has made significant progress along many fronts. At the same time, the demands placed on computing and the cyberinfrastructure have increased dramatically, raising many new critical RE research questions. For these reasons, it is an exciting time to be involved in RE research. Technologies that make significant advances in solving these problems are likely to lead to paradigm shifts that will impact many future generations of developers, computing systems, and the ultimate stakeholders – consumers.

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