

Requirements Development in Scenario-Based Design

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Abstract—We describe and analyze the process of requirements development in scenario-based design through consideration of a case study. In our project, a group of teachers and system developers initially set out to create a virtual physics laboratory. Our design work centered on the collaborative development of a series of scenarios describing current and future classroom activities. We observed classroom scenarios to assess needs and opportunities, and envisioned future scenarios to specify and analyze possible design moves. We employed claims analysis to evaluate design trade-offs implicit in these scenarios, to codify the specific advantages and disadvantages in achieving requirements. Through the course of this process, the nature of our project requirements has evolved, providing more information but also more *kinds* of information. We discuss the utility of managing requirements development through an evolving set of scenarios, and the generality of the scenario stages from this case study.

Index Terms—Participatory design, scenario-based design, requirements engineering, requirements development.

1 INTRODUCTION

THE traditional “waterfall” model of the system development process conceives of requirements gathering as a single step. Users, customers, and/or marketing representatives meet with designers, and describe what they want and/or react to what is proposed. Contemporary “iterative” conceptions of the development process take a more expansive view of requirements gathering (e.g., [3]). They emphasize the refinement and redesign necessitated by *emergent* requirements—requirements caused by interactions of features in the design, or by the accommodations of user practices to a new piece of technology, which in turn alter user requirements (i.e., the task-artifact cycle [7]). In this view, requirements analysis may recur cyclically through the system development process, but still as a more-or-less discrete step.

Participatory design contemplates a more substantial process of users and designers working together during an extended period of engagement to exchange perspectives, to learn about each other’s skills and values, and to jointly identify an appropriate set of requirements (e.g., [21]). Writing on participatory design often conflates requirements gathering with other system design activities, but much of the interaction among users and designers is typically directed at identifying and clarifying objectives of the design work [24].

What is the nature of this process of requirements gathering in participatory design? It is of course likely that a more extended, more intensive, and more empathetic process of collaborative requirements work will entrain more detailed, more insightful, and more accurate requirements. But is this merely a matter of accretion, of more requirements effort yielding better requirements results? We suggest that there is more to it than this. Through analysis of a case study, we will describe the process of collaborative requirements gathering in participatory design as “developmental” in the sense of Piaget and Inhelder [29] and Vygotsky [38]: requirements emerge through design activities; different design activities evoke different views of the requirements, and different requirements. In this paper, we use the term *requirements development* in a narrowed sense to refer to this developmental process.

We understand requirements to be statements about situations of use: Extant situations which implicitly describe human needs and opportunities for new tool support, as well as envisioned situations, enhanced, and perhaps otherwise transformed, by a design intervention [41]. The process of requirements development is a process of developing and refining a set of situation descriptions. Its typical starting point is a description of an envisioned situation that is somewhat wishfully incomplete and somewhat loosely grounded by a description of extant situations that is at least partially incorrect. Its ideal ending point is a detailed description of an envisioned situation explicitly grounded in an analysis of extant situations and sufficiently articulated to provide technical guidance for system specification.

2 THE TASK-ARTIFACT CYCLE

Our work is based on an analysis of human-computer interaction as a co-evolution of tasks and artifacts [7], [8]. We see scenarios as a vocabulary that can span both description of existing tasks, incorporating existing technology, and of

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future tasks, incorporating envisioned technology [9]. Scenarios describe the motivations and experiences of users as well as the events of human-computer interaction. Thus, scenario-based design can be a means for designers to manage the task-artifact cycle in order to achieve greater usefulness and usability [10].

We developed a method of scenario analysis in which the potential consequences for users that a scenario describes are explicitly enumerated in terms of positions taken concerning usability trade-offs. For instance, an example-based programming environment takes the position that the benefits of specific code examples outweigh costs of documenting the examples and potential downsides of erroneous generalization of examples. Our approach—claims analysis—represents applications and user interfaces as sets of feature-based trade-offs, each under the scope of a user interaction scenario, and supplemented by links both to specific empirical backing for the positions taken and to relevant scientific principles for human-computer interaction [12].

Our conception of scenarios contrasts to some extent with other current methods. For example, use cases specify sets of possible event traces (i.e., use case instances) [22], [39]; they eschew description of user motivations and experiences, and do not address usefulness and usability. In cooperative design, scenarios are used to characterize work flow and breakdowns, and are employed as conversational props in user-developer workshops [21], [24]; they are not cognitively articulated (e.g., in terms of user goals, expectations, and reactions) and are not taken as scoping contexts for design rationale.

Our method has been successfully applied to a variety of HCI design problems, including a tutorial [11], two programming environments [10], a task browser [2], a software design environment [30], an intelligent tutoring system [32], a multimedia authoring tool [6], and a World Wide Web site [19]. Here we investigate a more extended sociotechnical development process involving a diversity of stakeholder interests (in particular, a tension between clients and users), physical constraints, organizational complexities, and a particularly strong workplace culture that has historically resisted technological intervention [37]. Such a context provides an excellent opportunity to study requirements development.

During the past three years, we have worked with high school and middle school teachers to design a virtual physics laboratory. We adopted a scenario-based approach: we developed a future scenario, inventoried extant classroom scenarios, analyzed observed scenarios, and designed and prototyped new classroom scenarios. In the balance of this paper, we review this collaboration from the standpoint of how requirements were developed from these participatory activities. In our discussion the term “design team” refers to the ensemble of public school teachers, human-computer interaction specialists, and software technologists. However we will not analyze the participatory nature of our design case per se; we have done this elsewhere [17], [18]. Our concern is more specific: We want to examine how requirements were developed from scenarios in particular participatory design activities.

3 OUR STARTING STATE: NATIONAL NEEDS, PRIOR WORK, TECHNOLOGY

Our project began to take shape in early 1994. A large interdisciplinary group of Virginia Tech faculty had been meeting through the Winter and Spring, sometimes with teachers and administrators from the county public school system, to discuss project concepts exploiting the Blacksburg Electronic Village (BEV). The BEV is an advanced community network project [13]; at that time, T-1 Ethernet was being run to several county schools, enabling many new opportunities for school activities exploiting Internet and community resources.

These discussions focused for the most part on nationally-articulated needs in public school (K-12) education, such as supporting collaborative, project-based learning in K-12 classrooms, increasing community involvement with schools, improving access of rural schools to educational opportunities, enhancing gender equity in science and mathematics education, and controlling material costs (Fig. 1; see also [1], [28]). We obtained a planning grant from the United States National Science Foundation (NSF), which allowed us to provide several teachers with networked classroom computers, and to continue and expand our discussion process.

Through this process, several of us became quite interested in pursuing collaborative learning with computer networks as a participatory design activity with teachers [40]. Several projects were initiated; the most extensive of these was a computer science PhD dissertation consisting of ethnographic studies of participatory design with teachers in which several structured asynchronous discourse applications were developed [25]. Thus, during the latter half of 1994, the project of supporting collaborative learning through participatory design of networked educational software was already underway. In the Fall of 1994, we developed the scenario in Fig. 2 as part of a grant proposal to the National Science Foundation.

This scenario (we call it the “Marissa scenario”) was written to convey our starting vision of computer-based collaborative learning. It is a “client” scenario (in Checkland’s [16] term, “owner”), directed at the goal of securing resources. It addresses key issues in educational technology (Fig. 1) through a vivid example of how the BEV infrastructure could enhance education in local schools. The NSF reviewers found this vision inspiring, and authorized over \$1,000,000 to help us realize it. The Marissa scenario became a touchstone for our project. It has guided the development of our technical plan, and helped to build consensus among the constituencies of our team, the teachers, and university faculty and students from various departments.

The Marissa scenario instantiates our initial top-level requirements. The activity in the scenario is collaborative and project-based; the students construct and analyze a series of simulation experiments, learning self-initiative and socially constructive approaches by engaging in them. In our proposal, we suggested that community members—parents for example—could also visit this virtual laboratory, and thus more easily become involved with school activities. We thought of this as an on-going “science fair” accessible via the Blacksburg Electronic Village community network.

- Support collaborative, project-based classroom learning
- Increase community involvement in public schools
- Improve access of rural schools to educational opportunities
- Enhance gender equity in science and mathematics education
- Reduce equipment costs and handling

Fig. 1. Initial top-level requirements (drawn from our National Science Foundation grant proposal, April 1995).

- Marissa, a 10th-grade physics student, is studying gravity and its role in planetary motion. She goes to the virtual science lab and navigates to the gravity room.
- In the gravity room she discovers two other students, Randy and David, already working with the Alternate Reality Kit [33], which allows students to alter various physical parameters (such as the universal gravitational constant) and then observe effects in a simulation world.
- The three students, each of whom is from a different school in the county, discuss possible experiments by typing messages from their respective personal computers. Together they build and analyze several solar systems, eventually focusing on the question of how comets can disrupt otherwise stable systems.
- They capture data from their experiments and display it with several visualization tools, then write a brief report of their experiments, sending it for comments to Don, another student in Marissa's class, and Ms. Gould, Randy's physics teacher.

Fig. 2. Envisionment—the Marissa scenario (Fall 1994).

The scenario describes three children collaborating across the county—the funded project included four schools, two from Blacksburg and two from a rural portion of Montgomery County. In the scenario Marissa is an equal participant with the two boys; perhaps it is not so salient to her or to them that there even is a gender difference [34]. We also emphasized how the virtual laboratory could save school resources with respect to equipment costs and handling; interactive simulations would not get used up or worn out, and could be easier to set up.

During the early months of 1995, our large, interdisciplinary group developed a proposal, and won a major award from the National Science Foundation. By then we had been working with teachers and other school personnel for a year to articulate high-level requirements and envision a technical approach.

4 CLASSROOM CONTEXT

When our project officially started in January 1996, we focused on developing a detailed description and understanding of typical activities in the teachers' science classrooms. This was a critical step toward creating an effective participatory design relationship in this distinctive socio-technical setting: We needed to better understand the classroom context—the teachers' work practices and their beliefs about teaching, how the classroom and its artifacts are used in teaching, the interactions among students and between students and teachers; the teachers needed to better understand our research and development interests and activities as they would appear in the classroom setting. Most importantly, we all needed to work together to achieve these objectives.

Through the Spring, we conducted an ethnographic study of the four classrooms: We carried out questionnaire and interview studies with the teachers and their students, we spent many hours observing and videotaping classroom activity, and we collected a variety of educational artifacts

such as lesson plans, science journals, etc. Guided by the Marissa scenario, we focused especially on learning situations that involved student discovery and peer collaboration. We applied the ethnographic methods of Fetterman [20] to analyze these materials [17]. This analysis identified major categories, distinctions, and themes present in the classroom practice, allowing us to ground our requirements in these abstractions.

The scenario in Fig. 3 is a representative example of the science learning activities we observed in the middle schools. It summarizes a lesson on waves given by one of the middle school teacher-participants, incorporating a set of learning activities that take place over a four-day period. This observed scenario reveals several things of interest about this particular teaching situation. For example it illustrates the usefulness of combining and blending different teaching techniques (e.g., didactic discussion, guided discovery, demonstration) across complementary learning activities. It also identifies a range of activities that can be used to promote collaborative learning (e.g., the class discussion, the small group slinky manipulation, the group poster presentations). Finally it emphasizes the important role of physical interactions with equipment, especially within this age group.

The results of the ethnographic analysis challenged our initial project vision. For example, we found that classroom space is very congested; rooms are filled with tables, equipment, and other materials. Our initial vision implied that each student would have his or her own computer; our project budget provided funds for this. However, there just did not seem to be enough space for one computer per student. We found that teachers employ a variety of instructional styles, from traditional didactic to unstructured discovery. They blend these dynamically and idiosyncratically. Our project vision emphasized student-driven discovery learning, but the classroom context reminded us that whatever we developed would need to accommodate other styles as well. Fig. 4 summarizes some of our classroom observations (for a more complete discussion, see [17]).

- In Ms. Gould's middle school science class, each student describes in his/her science journal the waves he/she knows about, along with related facts or ideas. The students then share their individual work in a discussion guided by the teacher.
- Groups of 4-5 students experiment with a large wire slinky. Their manipulations are guided by an assignment sheet that tells them how to generate different kinds of waves, as well as questions aimed at guiding their exploration of the waves' characteristics. Each group collects observations on the waves it generates, with the teacher circulating among groups to guide students' manipulations of the slinky and attention to interesting aspects of the resulting waves.
- Each group develops a short poster presentation using large sheets of paper and felt-tip markers. They describe the waves they generated and the wave characteristics they noted. The groups then deliver their poster presentations to the rest of the class, with the teacher taking an active role in critiquing each group's findings and in directing class discussion.
- After sharing their presentations, students read material from their science textbook that introduces formal terminology for waves and wave properties. They are also given homework in which they write down definitions for various terms. This homework is submitted and discussed in class.
- The final element of the lesson is a demonstration of how sound waves are transmitted through different media (e.g., solids, liquids, gases). The teacher uses an assortment of musical tuning forks in combination with objects and surfaces in the classroom (e.g., air, the floor, a table).

Fig. 3. Classroom context scenario, a lesson on waves (Spring, 1996).

- Classrooms are filled with tables, equipment, and other materials
- Teachers idiosyncratically recruit and blend different teaching styles (e.g., didactic and discovery)
- Students collaborate on a variety of tasks (e.g., manipulating apparatus together, coaching one another)
- Students use various collaborative techniques (e.g., consensus-building, mentoring, initiative-taking)
- Teachers employ many exercises; much time and attention is spent on manipulation (middle school) and laboratory technique (high school)

Fig. 4. Example classroom observations (Spring 1996).

We observed that students frequently work on laboratory exercises in groups. Indeed, this organization is highly over-determined: schools do not have enough equipment or space for each student to have his or her own set-up, teachers would not have the time to manage so many set-ups, and collaborative learning is valued by teachers and motivating for students. We saw that students collaborated on many kinds of tasks: students organize themselves into groups and organize their groups, they manipulate equipment together, they gather and record data, they discuss interpretations, create and deliver presentations, and they coach one another as necessary. We observed several kinds of collaborative interaction, for example consensus building during group conflicts, impromptu mentoring by the more prepared students, and initiative-taking in making and executing experimental plans. These observations made salient to us that different kinds of collaborative tasks and interactions might need to be supported differently. They also emphasized potential contrasts between co-present collaborators and remote collaborators; our initial vision had focused only on the latter.

The classroom observations also validated and refined aspects of the project vision. For example, we found that students worked with a variety of physical materials, such as carts on tracks to study inelastic collisions in high school and slinkies to study wave motion in middle school. Particularly in high school, students used standalone sensors-and-calculator ensembles, for example, to measure and graph velocities of moving bodies. A huge amount of time was spent setting up, calibrating, and manipulating this equipment.

This analysis of the classroom context helped to elaborate our initial requirements, to add requirements to our analysis, and to prioritize requirements. For example, we detailed the requirement to support collaborative learning (Fig. 1) by articulating a variety of collaborative tasks and techniques. But the emphasis on specific classroom settings and activities also brought to light new requirements, for example, those of managing a very constrained and cluttered classroom space, and of supporting a variety of teaching styles.

The study of classroom activity also caused us to background our initial concern with community involvement. To some extent this was a matter of capacity: immersion in the school context took all of our resources. But there may be more to it than that. Classrooms are not well-integrated with the larger community, and we made an explicit commitment to enter into the extant classroom culture. To build an effective participatory relationship with the teachers, this was absolutely the right thing to do. But it also infused our project with the conservatism of classroom culture. For a long time, we simply stopped talking about community-involvement objectives such as the virtual science fair.

5 TRADE-OFFS IN CLASSROOM ACTIVITIES

During the Summer of 1996, we began a more analytic and theory-driven phase of the project. The entire design team spent two weeks in a workshop, reviewing and analyzing the ethnographic data collected in the classrooms during the Spring and making further plans. A central activity in this workshop was a detailed analysis of selected video-

taped classroom scenarios. We selected learning episodes that provided good coverage of the distinctions extracted in our ethnographic study of the classroom context (e.g., variety in teaching styles and forms of student collaboration, see Fig. 4). We also tried to select scenarios that seemed to be typical examples of science learning activities, and that covered both the middle school and high school science learning activities. One of the scenarios selected was the middle school wave lesson described in Fig. 3; a second is the high school lab on inelastic collisions described in Fig. 5.

We spent several days in participatory analysis: as a group (four teachers, four HCI designers, four software developers) we used claims analysis to identify salient features in these scenarios, and the desirable and undesirable consequences of these features for students [18]. For example, two salient features of the inelastic collision scenario in Fig. 5 are the individual initiative-taking displayed by Godfrey, followed by Matilda's efforts at conflict resolution and consensus-building. The team identified these features and considered the potential pros and cons of both collaborative styles (see Fig. 6). This produced a much more articulated analysis of the impact of various leadership and collaboration styles, rather than a simple focus on gender equity (recall Fig. 1).

Another major issue that emerged in participatory analysis was the relationship of classroom activity oriented around physical equipment to activities envisioned for the virtual laboratory. For example, as part of the inelastic collision lab, students must set up railings, carts and photogates; this prompted an extensive discussion of the consequences of equipment set up, calibration, measurement and error. Such activities include opportunities to develop and refine many laboratory skills. The physical manipulation and shared physical activity is both intellectually stimulating and consonant with collaborative learning: Students must organize themselves into effective groups to perform these exercises. Two of the teachers demonstrated a velocity sensor, and suggested that the data generated by the sensor could be integrated with the tools we were building for the virtual laboratory.

Our ethnographic studies had revealed that physical lab equipment was an integral part of the typical science classroom, but the claims analysis helped us more fully understand its pedagogical role and impact. Specifically, we hypothesized that the use of physical equipment is valuable in science education because it conveys authentic, scientific practice, teaches general mechanical skills, places science concepts in a physical context, and presents an opportunity for students to negotiate roles and to work together. In contrast, our analysis also suggested that the use of physical equipment may be detrimental to science learning because students may find set-up and execution to be tedious, teachers may require extensive preparation to deploy the equipment, and the physical experiment may detract, confuse, or de-emphasize the underlying science concepts.

Our initial vision assumed one computer per student. The teachers had been enthusiastic about this plan, but our classroom observations suggested that there may be no place to put so many computers. The participatory analysis now led us to view this as a set of pros and cons associated

with equipment scarcity: What was salient to the teachers is that their students do not have adequate access to computers. When our project began, they had five computers among the four of them, and the best two of those computers had been provided just the year before by our planning grant. However in analyzing trade-offs we also identified positive consequences of having fewer than one computer per student. For example, shared equipment can evoke cooperation such as we had seen in the classroom activities.

At the same time, we realized that groups of students could not easily work together using the computers currently in the classrooms. The displays on these machines were small; only one student in a co-present group could type at a time. Group interaction we observed involved several students talking at once, accompanied by pointing and gesturing. This would be poorly conveyed by any text-only communication mechanism. These considerations about classroom space and collaboration reinforced a growing sense that we needed to provide relatively high-bandwidth interaction for the virtual laboratory.

The two lines of discussion came together in the recognition that purchasing a smaller number of machines would allow us to design activities that take advantage of large displays, extensive memory, and good multimedia support. Larger displays could facilitate sharing of computers by multiple students; video conferencing could provide a mechanism for integrating physical and computer-based activities: remote collaborators could directly show and tell about what they were doing.

Our discussion of trade-offs in classroom provided yet another source of input into the project's developing requirements. The ethnographic analysis had documented categories and distinctions of the extant classroom context. The subsequent analysis of trade-offs in selected scenarios caused us to more deliberately consider the likely impacts of specific features of the classroom activity, leading us to further elaborate our requirements, in sometimes surprising ways: We began to understand the issue of gender equity as involving differing approaches to leadership and collaboration, each with its own pros and cons. We came to understand the value of physical manipulation, and thus to see equipment handling and set-up as more than merely a distraction from real learning (Fig. 1). By analyzing collaboration requirements as situated in the space-constrained and animated classroom setting, we came to see the need for a higher level system platform. At the same time, this participatory process provided a mechanism for the diverse members of the project team to interrogate the rationale for, and achieve consensus about, our requirements.

6 ACTIVITY DESIGN

In late Summer and Fall of 1996, we began the transition from analysis to design: we planned and carried out a series of classroom activities to explore the usefulness and usability of various networking mechanisms we expected to incorporate into the virtual laboratory (e.g., shared whiteboards, video conferencing, voice chat) and a physics simulation for studying energy and motion on an inclined plane. These activities were also designed to address usability trade-offs we had identified, testing and refining our

- In Mr. Neidermeyer's high school physics class, students experiment with collisions of miniature cars sliding along a metal rail; the cars have latches which cause them to join when they collide. The students use photogate sensors to measure the initial and final velocities of the cars, comparing their data to ideal results calculated from an inelastic collision equation. They know that during the collision energy is transferred from the moving car to the joined pair of cars, and that this energy transfer is observed as a decrease in velocity between the first car and the pair. Their goal is to obtain an experimental result within 3 percent of the ideal; they run trials until they reach this 3 percent error threshold, adjusting experimental parameters (e.g., force of initial car, distance between the photogate sensors measuring velocity) as necessary.
- Matilda, Dexter, Hildegardé, Esther, and Godfrey execute the lab collaboratively: Dexter collides the two cars along the rail, Godfrey catches the two cars after they travel beyond the photogate sensors, and Matilda reads and announces the velocity measurements.
- After approximately a dozen runs of the experiment, the group has been unable to achieve the 3 percent threshold. At this point, Godfrey believes that the photogates are too far apart. He moves the two photogates closer together and positions the two cars for another run.
- Looking over the results of previous runs, Matilda suggests, "You know what?, maybe if we increase the distance..." Before Matilda completes her sentence, Dexter interjects with, "Yes, we should!," and grabs one of the photogates to slide it further down along the ramp. Grabbing the same photogate, Godfrey objects, "No, I want to put them closer." Dexter argues, "No, we just put them closer and we got a 43 percent error." Pushing Dexter's hand away and re-setting the photogates, Godfrey continues, "We didn't put them close enough."
- Matilda makes a suggestion and seeks group consensus: "We should go around in a circle and have our own theories and we'll test them out and see who gets the lowest. You guys want to do that?" Both Esther and Hildegardé approve; Godfrey and Dexter grudgingly agree.

Fig. 5. Scenario analyzed for usability_trade-offs in classroom context, a lab on inelastic collisions (Spring, 1996).

- Consensus-building ensures that all ideas are considered and enhances group dynamics and the self-esteem of members, *but* requires a selfless and energetic leader and may be inefficient and/or inconclusive.
- Individual initiative-taking is efficient, challenging, and provides opportunities for group members to play leadership and supporting roles, *but* requires an assertive leader, may fail to evoke or consider the group's best ideas, and can demotivate or annoy group members
- Focus on physical equipment set up, calibration, measurement and error conveys authentic scientific practice, teaches general mechanical skills, puts concepts in context, and provides an opportunity to negotiate roles and work together, *but* can be tedious for students, may require extensive preparation from the teacher, and may confuse or de-emphasize underlying concepts.
- Few equipment stations in the classroom take up little classroom space, and encourage cooperative learning interaction among students *but* the capabilities of computers (etc.) may be inadequate for meaningful group work, the teacher must manage access to equipment, and any given student may have limited access to the equipment.

Fig. 6. Requirements evoked in analysis of classroom scenarios (Summer 1996).

scenarios and claims analysis [12], [18]. For example we developed an activity where simple physical labs were carried out by middle school students, but the process was managed through video conferencing by high school student mentors rather than by teachers (compare the fourth activity summarized in Fig. 7 with the third claim in Fig. 6).

During this design phase a critical new requirement became apparent: Remote collaboration must be justified in the goals of the activities; even children quickly grow tired of merely novel communication experiences. We did not want to arbitrarily demand that students from different school sites work together; we wanted them to see and experience the benefit of doing so. This helped us to recognize an unarticulated dependency in the Marissa scenario (Fig. 2). Marissa's collaboration occurs *outside* the classroom context; for her, the virtual laboratory provides access to peers that she might not otherwise have. However, our design focus by this stage was on *classroom* activities where peer collaborators are always available. Our classroom studies

had identified and analyzed many types of collaboration among students, but because no network technology had been in use, none of the collaboration involved remote interactions between students in different classes. We could not recognize this requirement until we began designing remote collaboration activities.

The mentoring scenario in Fig. 8 describes an activity developed to motivate synchronous remote collaboration. We expected the high school students to benefit from preparing themselves and coaching the younger students, and the middle school students to enjoy interacting with the older students. Further, we expected these benefits to outweigh the costs of learning the technology, establishing and maintaining network connections, and the background noise and distraction of concurrent sessions and activities. Other activities we developed for justifying remote collaboration involved the pooling of resources or data, where contributions from students at two school sites are required to complete an experiment (see activities 2 and 3 in Fig. 7).

- *Internet search.* Middle and high school students search the Internet for sites containing motion data, organizing their finds in a shared repository. From the collected data, students construct graphs to illustrate the concepts of distance, velocity, and acceleration.
- *Data pooling.* High school students collaborate on the collection of data from a computer-based inclined plane simulation. After experimenting with various objects sliding down a ramp, groups of students are paired across two different high schools and communicate using text chat, synchronous audio, and video teleconferencing. Collaborating groups negotiate the division of duties, pool the data produced from different runs of the simulation, and then reflect on and analyze the overall results.
- *Comparing experimental findings.* Middle school students collaborate to compare findings from a melting/freezing point experiment. Groups of students are paired across two schools and communicate using text chat, synchronous audio, and video teleconferencing. Each group is given one of two possible substances. Collaborating groups compare the findings from their lab experiments in an attempt to determine which group had received which substance.
- *Physical experiment mentoring.* High school students guide middle school students in the execution of several intriguing equilibrium experiments. Through video teleconferencing, the high school students teach the middle school students the steps of the physical experiments as well as the underlying physics concepts inherent in the experiments.
- *Scientific issues debate.* High school students debate various scientific ethics issues using e-mail. High school teachers pose a set of scientific ethics questions to the class. Mailing lists are formed around each question as students engage in on-line debates.
- *Integration of physical equipment.* High school students collect path data describing a pendulum in motion using a motion-sensor, using the output of the sensor as direct input into a Java applet that creates a simple two-dimensional plot.

Fig. 7. Sample designed classroom activities (Fall 1996).

- High school students mentor groups of 3-4 middle school students on a force and motion exercise, using a computer simulation and other tools such as an electronic whiteboard, a video teleconferencing package, a spreadsheet, and an Internet-based application for storing and viewing questions and answers.
- Because the middle school students do not have enough computers for all students to participate at once, the teacher sets up two activities: half of the groups work with the mentors, the other half run a "matchbox" car experiment, exploring many of the same concepts demonstrated by the simulation.
- Terri, a high school student has been assigned to mentor Mert, Ethel and Sandy. Prior to the session, she familiarizes herself with the simulation and uses an Internet forms-based question-and-answer application to prepare a set of questions to guide her interactions with the younger students.
- During the session, Terri meets and communicates with Mert, Ethel, and Sandy using a video teleconferencing package. She guides the students through the use of the simulation, running through the steps of the simulation on her computer and describing the process as she proceeds. She occasionally picks up the camera and aims it towards her screen to show the state of the simulation on her screen. Sometimes she copies a snapshot of her screen onto an electronic whiteboard and annotates interesting features.
- Next, Terri directs the group to the prepared questions. The group answers the questions by experimenting further with the simulation, entering their answers into the forms provided. Terri stays on-line to provide further guidance as needed.
- When the students have finished Terri's questions, they discuss their answers with Terri over the video conferencing channel. For incorrect answers, Terri sends the group back to the simulation with guidance on how to find the correct solutions. After Terri and the group are satisfied with the set of answers, the questions and answers remain on the network for later review by the two teachers.
- After performing both the simulation and matchbox car exercises, each group develops a poster that describes its experiences, findings, and conclusions. The poster is presented to the class during a scheduled "presentation" day.

Fig. 8. Activity designed to include mentoring by high school students (Fall 1996).

The imperative to justify the use of technology in the goals of the activities led us to reconsider other features of the Marissa scenario as well (Fig. 9). For example, the Marissa scenario emphasized collaborative interactions with a computer simulation. However as we discussed the nature of learning from simulations, we recognized that simulations are effective when they are experienced as analogs of *real* situations, and that they can play a special

role in allowing students to explore difficult boundary conditions of real situations. Experimentation with real objects moving on inclined surfaces allows students to map abstract concepts to real world phenomena, whereas simulations allow exploration of boundary conditions such as frictionless surfaces. The combination of the inclined plane simulation with the physical ramp experiments in the "Data Pooling" activity (see Fig. 7) was an effort to promote

- Synchronous remote collaboration must enhance classroom science activities (e.g., as when contributions from another site are needed to complete the activity).
- Computer simulations should complement rather than replace physical experiments.
- Fewer computers than work groups entails that classroom activities coordinate computer and noncomputer elements.
- New classroom activities using computer technology must be integrated with existing curriculum objectives.
- Effective collaborative activity requires prefatory social grounding.

Fig. 9. Requirements discovered through activity design (September 1996).

these complementary roles, as was the pendulum path lab in which students used motion sensor data as input to a Java graphing applet.

As the details of the classroom activities were developed, we also became more attuned to issues of classroom management. For example, we recognized that our earlier decision to install only a small number of computers in each room now created a new requirement to provide concurrent activities for the noncomputer-using students. In the inclined plane lab, this was accomplished by having groups of students switch between the physical ramp activities and the simulation. In another example, middle school students rotated through eight experiment stations to explore a set of equilibrium phenomena (see the fourth activity in Fig. 7). At three of these stations, high school students served as remote mentors, interacting with the younger students via shared whiteboards and video conferencing.

Our design deliberations for the new classroom activities also brought to light a higher-level integration requirement—the computer-based activities must contribute to existing science curriculum objectives. The new experiences should support other skills and knowledge the students are expected to acquire. For example, a requirement for the inclined plane simulation was that its output could be imported into a conventional spreadsheet, because spreadsheet-based graphing and analysis of data were among the science curriculum objectives.

In some cases the design work raised requirements for unanticipated lesson components. For instance, the teachers felt that their students would need to establish a social foundation in the networked situation before they could collaborate effectively. They believed that this would be especially true for the middle school students who are more distracted by social dynamics. This social grounding requirement had been invisible in our studies of the classroom, because it is satisfied implicitly in face-to-face classroom interaction.

We began this design phase with the goal of exploring collaboration technology options. Our design of classroom activities that could exercise the technology again evoked new views of existing requirements and new requirements; for the most part these focused on making the interventions a meaningful component of the teachers' curriculum goals and on integrating the changes with their extant educational approaches.

7 SCHOOL PRAGMATICS

When we implemented the Fall scenarios in the classrooms, we discovered further requirements arising from situated

classroom usage. A particularly significant and nasty example pertains to class scheduling: The schedule of class periods is not the same, even among the schools in a single county system. Despite the efforts of the School Superintendent and the principals, we were unable to schedule completely overlapping classes among our four classrooms; we had to settle for partial overlap, achieved in part through ad hoc adjustments (e.g., bringing two classes together over their lunch periods). We learned that class scheduling is more low-level and local than we could have expected. In general, one cannot work only through official lines of organizational management [35].

The revised mentoring scenario in Fig. 10 illustrates ways in which the design team responded to the problem of partially-overlapping class schedules: the collaboration takes place over an extended period, with project groups forming and then collaborating over a period of months rather than a day or two. The synchronous collaboration itself is comprised of relatively brief interactions, but this work is embedded within a number of related asynchronous exchanges. The scenario makes clear the distinction between work that truly requires synchronous communication (e.g., the initial meeting of mentor and students; guided use of a simulation) and work that can be supported by asynchronous communication (e.g., Web-based question and answer). More generally, the scenario illustrates the requirement that synchronous activities must be supplemented by and integrated with asynchronous activities.

The need to incorporate asynchronous collaboration with synchronous collaboration was just one of the pragmatic requirements discovered in fielding the new classroom activities; Fig. 11 summarizes others. Observing video conferencing, voice chat, shared whiteboards, and text chat use in the physical classroom setting impelled us to focus on relevant physical characteristics: We had designed concurrent non-computer learning activities, but in practice, the noise created by these other activities, and by voice chat and video conferencing, caused significant problems with audio quality and feedback. The students tried to accommodate by passing microphones from person to person (instead of leaving them mounted on top of the displays), and by bending around or leaning into the speakers. We recognized in this a need for local sound-damping (e.g., headsets) and/or improved sound quality (e.g., better microphones); the students themselves often simply resorted to communication over the shared whiteboard or text chat. The scenario in Fig. 10 relies on an interim solution—moving the noncomputer activity out of the classroom.

We also drew several more narrow requirements. In a high school activity involving our inclined plane simulation, the two classes participating were unequally prepared,

- High school students mentor groups of 3-4 middle school students on a force and motion exercise, using a computer simulation and other tools such as an electronic whiteboard, a video conferencing package, a spreadsheet, and an Internet-based application for storing and viewing questions and answers. Since class periods at the middle and high schools do not completely overlap, the mentoring occurs in 30 minute intervals during which the middle and high school periods overlap.
- Because the middle school has only three computers, the teacher limits participation to a portion of the class. Those groups assigned to the simulation exercise are given five days to work on the computers—three of those days will involve collaboration with their high school mentors. The other groups run a related physical experiment using “matchbox” cars to explore many of the same concepts demonstrated by the simulation. To minimize background noise, students not using the computers work in the hallway.
- Terri, a high school student has been assigned to mentor Merty, Ethel and Sandy. Prior to the session, she familiarizes herself with the simulation and uses an Internet forms-based question-and-answer application to prepare a set of questions to guide her interactions with the younger students.
- Terri meets Merty, Ethel, and Sandy in their first video teleconference; Terri and the group become familiar with each other and with the software. They experiment with the mike, video image, speakers, and whiteboard.
- During the next session, Terri guides the students through the use of the simulation, running through the steps of the simulation on her computer and describing the process as she proceeds. She occasionally picks up the camera and aims it towards her screen to show the state of the simulation on her screen. Sometimes she copies a snapshot of her screen onto an electronic whiteboard and annotates interesting features.
- Over the next couple of days the middle school group continues to experiment, referring occasionally to Terri’s questions. They enter their answers to the questions into the forms provided. When they need help, they send e-mail to Terri, who checks her e-mail daily and responds.
- At the third mentoring session, Terri and the students discuss their answers. For incorrect answers, Terri redirects the group back to the simulation and gives them further guidance on how to find the correct solutions. After Terri and the group are satisfied with the set of answers, the questions and answers are retained on the Internet. Later, Ms. Snodgrass and Mr. Neidermeyer review the questions and answers to evaluate the performance of their students.
- After all the groups have completed their activities, each computer-based group is combined with a physical experiment-based group. The groups discuss their experiences and develop a poster comparing experiences, findings, and conclusions. The poster is presented to the class during a scheduled “presentation” day.

Fig. 10. Mentoring scenario revised in response to pragmatic issues (Spring 1997).

- Partially-overlapping class periods entail that synchronous collaboration mechanisms be supplemented with asynchronous mechanisms
- Ambient noise in classrooms (caused by students engaged in noncomputer activities as well as by students using voice chat) entails a need for local sound-damping (e.g., headphones)
- Variations in the preparation or experience of scheduled collaborators may evoke unexpected types of collaboration (e.g., mentoring), and entails supporting a variety of collaborative exchanges
- Providing multiple computer tools (e.g., a simulation and a whiteboard) entails easy sharing and annotation of information from one tool to the other

Fig. 11. Requirements emerging from activity implementation (Fall 1996; Spring 1997).

despite considerable planning and coordination. One class had practiced extensively with the simulation, and had been primed for the collaborative exchange, whereas the second had fallen behind schedule and had only a few minutes of preparation on the day of the experiment. This helped us recognize that classroom activities, and not merely course schedules, have to be synchronized for effective remote collaboration. However, there is inherent variation in the time required for classroom activities, and this limits how closely two teachers could ever coordinate their preparation for collaborative endeavors. In this case, we observed one group of the more-prepared students spontaneously mentor a group of the less-prepared students. This interaction appeared to be beneficial to both groups, and emphasized to us the need to expect and support this particular type of ad hoc collaboration.

We also observed an important requirement for integration among the various computer-based tools themselves. Students moved frequently from one tool to another (e.g., from the simulation to the shared whiteboard), and wanted to be able to bring their working context with them. To some extent they were able to cut and paste material from one source to another, but the sharing was awkward and sometimes impossible.

8 CURRENT REQUIREMENTS FOR A VIRTUAL LABORATORY

The goal of our scenario development and analysis work was to investigate and refine our initial vision of collaborative learning in a virtual laboratory—to more accurately understand the requirements implicit in extant classroom situa-

tions, and to more comprehensively articulate envisioned situations that could address their issues. The scenarios discussed in the foregoing sections illustrate the facets of this investigation, a variety of design activities evoking a variety of requirements. Fig. 12 summarizes the process relationships among the example requirements in Figs. 1, 4, 6, 9, and 11. The figure shows how the five initial goals of the project (Fig. 1) evolved through the stages of ethnography, claims analysis, activity design, and prototyping, showing how requirements were elaborated, discovered, dropped, or superseded. For example, our starting concern with facilitating participation by girls was elaborated into an analysis of collaboration possibilities and leadership styles. Our ethnography of the classroom helped us discover new requirements regarding teaching styles. Focusing on the classroom also led us to drop our original orienting concern with community involvement in education. Our initial goal of improving access to science for rural students through networking was superseded by the requirement that any remote collaboration be intrinsically motivated in the activity.

Although the "process view" in Fig. 12 is merely a summary of our case study, it suggests possibilities for future work. In particular, it would be useful to more formally differentiate types of steps in requirements development (elaborate, discover, drop, supersede), to model the knowledge underlying requirements at different stages, and to validate the resulting formalism with further cases.

A more summative view of our requirements development process can be seen in Fig. 13, which contrasts our initial vision with the result we reached. The right column in the figure narrates a revised Marissa scenario, a more explicitly detailed description of an envisioned situation.

The two scenarios contrast in many ways. The original scenario focused on relatively short term collaborative encounters that could arise spontaneously during exploration of a shared space, more like a multiuser domain (MUD) than a school laboratory. Our focus now is on sustained collaboration among students with a shared task (in this case, middle schoolers working on a gravity project). This shift reflects a more accurate understanding of the nature of school work, in which groups persist over longer time periods and collaborate to achieve task-oriented goals. Given scheduling and logistic constraints, we realized that it is rather unlikely that students from different classes would spontaneously form into coherent and effective groups to pursue goals that happen to simultaneously satisfy all their individual curricular needs.

The revised scenario also elaborates the possibilities for collaboration among science students, including cross age-level mentoring, and details a variety of distinct types of collaborative interaction—e.g., co-construction, resource sharing, demonstration, explanation, question-and-answer, review and critique. The original scenario focused almost entirely on shared exploration and analysis of a computer simulation, with brief reference to a shared report development.

The more extensive range of collaborative activities demands and exercises a greater variety of collaborative exchanges. Whereas before our focus was on students' synchronous collaboration with a computer simulation, the

new scenario includes this as just one type of interaction. Shared execution of the simulation is embedded within a series of extended asynchronous collaborations involving the construction of a physical model, the exchange of various email messages, the posting and answering of questions in a virtual notebook, and the shared creation and review of a lab report.

The original scenario previewed some of the integration we hoped to support, for example using visualization tools to analyze the output of a simulation. The new scenario envisions similar functionality, but emphasizes integration of activities and services throughout the collaborative project—e-mail used to set up video conferences, a computer simulation used to complement and extend a physical model, a virtual notebook that serves as both a source of teacher or mentor guidance and as a persistent and shareable record of results, reports and comments.

The requirements illustrated in the revised vision scenario of Fig. 13 provided technical guidance for the specification of the virtual laboratory. We are now implementing this specification, using a combination of a Java-based replicated architecture for synchronous collaboration activities (e.g., shared workspaces, simulations), standard tools for communication (e.g., NetMeeting® for video conferencing, a county-wide server for email), and a virtual notebook for project selection, development, and publishing [23].

9 SCENARIOS AND REQUIREMENTS

Scenarios can play a wide variety of roles throughout the development process [4], [24]. Their concreteness makes them accessible to the many stakeholder constituencies of a development project. Resultingly, they facilitate broad participation and make it more possible that a representative and effective diversity of relevant domain knowledge will actually be brought to bear on the design problem. Their vivid depiction of human activity promotes focused reflection on the usefulness and usability of an envisioned design intervention. This helps to ensure an early and technically detailed consideration of use, and the context of use, and mitigates the temptations and distortions of technology-driven development. Scenarios encourage designers to envision outcomes *before* attempting to specify outcomes, and thereby they help to make requirements more proactive in system development.

We developed the Marissa scenario (Fig. 2) as a means of exploring and understanding educational needs and opportunities identified or embodied in current research and in policy statements, including requests-for-proposal distributed by funding agencies (like the National Science Foundation's Network Infrastructure for Education program that funded our project) and local school system planning documents [26]. We used the scenario to integrate and illustrate a set of high-level objectives that made sense given the context of our own research interests and backgrounds, the national opportunities for new research programs, and the motivations and plans of the school and community. The scenario includes implicit rationale for this early vision, for example conveying why Marissa might

want to visit a virtual laboratory in the first place. Such details makes the scenario engaging and believable, helping to convince ourselves and prospective partners (the local schools, the Blacksburg Electronic Village, Apple Computer) that the various goals could be addressed in a complementary and coherent fashion. This was vital; we had to convince our "clients" in order to even get the opportunity to work with potential users.

The scenarios from our ethnographic studies were not generated in accordance with a vision, rather they were records of what we deemed to be significant episodes of learning activity—science lessons occurring over a period of hours or days. We also collected other forms of data at this point, interviews and informal observations, but the videotaped science lessons formed the core of our data. These scenarios revealed the complex interactions of collaborative learning and the organizational context of the school. For example, we characterized a range of student leadership styles, and recognized the diverse and idiosyncratic pedagogical and classroom management styles of the teachers [37]. The ethnographic studies provided domain knowledge clarifying some of our original goals, and calling into question others. In Zave and Jackson's [41] terminology, the Marissa scenario was purely "optative" requirements work, while our studies of classroom context were purely "indicative."

We selected representative scenarios from the ethnographic data for participatory claims analysis, identifying features of these situations that might have positive consequences (upsides) or negative consequences (downsides) for students or teachers [12]. These claims were used to document issues we wanted to address as the requirements development process moved from domain analysis to requirements for our new system—for example recognizing that while setting up physical equipment can be tedious and distract from a lesson's science content, it can also provide an opportunity for students to negotiate roles and work together. In Zave and Jackson's terms, this is a phase of requirements refinement; the trade-off analysis articulates rationale that is implicit in the initial indicative domain description to yield an indicative description more suitable to guide design (trade-offs individuated by particular features).

We designed new classroom activities to evoke further requirements, particularly with respect to the application of computer-mediated communication technologies (Fig. 7). This allowed us to explore requirements emanating from the technology to be used, but to do this within a context of meaningful classroom activities. Proposing features of new activities allowed us to investigate the applicability of the earlier trade-off analysis; claim features (e.g., setting up physical equipment, see Fig. 6) can become requirements if they can be incorporated into a design that favorably resolves the trade-offs. In Zave and Jackson's terms, activity design integrates the initial optative envisionment with subsequent indicative descriptions to yield a more articulated optative description.

We evaluated these classroom activity scenarios to expose external pragmatic constraints of the school context. The teachers have expert-level domain knowledge of organizational and operational characteristics of schools (Fig. 11), but as is typical in the workplace, this knowledge is

tacit, background knowledge [35]. Observing and analyzing these pragmatic constraints allowed us to address them explicitly as requirements.

To a great extent the requirements development process moves forward through these analysis, design, and evaluation activities; thus, our account has emphasized the interfaces and handoffs among adjacent phases. However, the process is also iterative and cumulative. In the 1997-1998 school year we are deploying and evaluating early releases of our virtual laboratory software. This has involved further refinement of our classroom activity; it has also involved further ethnographic data collection in the classroom, though now focused on designed situations of use, rather than on the situations that were extant prior to our project.

A by-product of this iterative and cumulative process is a collection of various kinds of scenarios and scenario analysis. This provides dividends in traceability, abstraction and reuse. Thus we have a living record of our design goals, detailed to various levels, recounting what requirements, domain knowledge, and constraints were apparent to us at various points in the process, what provisional decisions we took, and why. This archive provides stage-to-stage guidance as described above, but it also provides a description of the overall process; for example, it provides a resource to us now in specifying, fielding, and assessing the current virtual laboratory. The collection of scenarios and analyses can be abstracted and summarized to enhance its potential applicability to other projects [12], [15], [36].

10 TOWARD A FRAMEWORK FOR SCENARIO-BASED REQUIREMENTS DEVELOPMENT

The language of requirements engineering is permeated by the presumption that requirements are there to be "captured" or "gathered." Our case study is an example of a more extended requirements process. Through the course of a participatory design project that has already encompassed more than three years, we have experienced qualitative changes in our opportunities to learn about requirements from design activities. The client's original functional requirements (Fig. 1) were radically and continuously transformed. We have called this process requirements development—it progresses through a series of stages; through the course of these stages, qualitatively different requirements become accessible or salient; the work of prior stages is often prerequisite to the possibility of succeeding stages.

We do not see this merely as a matter of initially mistaken notions being subsequently corrected, or of more requirements work leading to successively finer decompositions. Our initial high-level requirements were not corrected; they are still a good statement of the overall project goals. And neither were they just hierarchically refined; new requirements emerged throughout our various design activities. Many of these were nonfunctional requirements pertaining to workplace practice—a category absent from standard taxonomies of nonfunctional requirements [31].

Our design context differs from the commercial software world: we are teachers and students who also design and evaluate new technology. Our projects tend to involve large but loosely-coordinated teams with soft deadlines. It is

easier for us to justify and attend to the goal of mutual learning through design collaboration than it might be for commercial designers. In our context, design knowledge is in many respects a more valued product than a designed and implemented system. We have the flexibility to explore and reflect upon methods. These qualifications having been voiced, we expect that taking requirements development as a significant and revelatory process pertains to system development in general.

The central implication of our analysis is the importance of planning for an extended and differentiated process of requirements development. This does not entail that the overall design process take longer. First, there is no need to conceive of requirements development as an independent and prerequisite stage or activity in system development, with respect to activities like design envisionment, prototyping, or even specification. Indeed, Brooks' [3] analysis of the development of the OS360 operating system showed (long ago) that such a linear dependency conceptualization is empirically unsound. Brooks' conclusion was that requirements identification might have to be reiterated after prototyping to capture emergent requirements. We are suggesting a more continuous process of requirements development, a process that spans all development activities up to and including specification. The different phases of analysis and design will lead to different views or types of requirements (notably, workplace practice requirements), and this requirements development process should be a planned element of the overall project.

Second, there may be a general structure to the process of requirements development that could be employed as a process template, a sequence of requirements-generating activities. We offer the stages in the right-hand panels of Fig. 14 as a proposed generalization of our case study.

Every development project receives some sort of initial charter or mandate; this may come from a customer, from customer surrogates, such as market analysts, or, as in our case, from sponsors. Every development project must insure that stakeholders agree on the project vision and initial directions. This makes it easier to recognize inaccuracies and incompleteness at later points in the process. Vision scenarios orient and focus the requirements devel-

opment process for the designers, vividly codifying the starting requirements set, and establishing a foundation of shared understanding.

Unless a development team includes workplace experts, it is unlikely to have access to adequate domain knowledge. However, giving workplace experts a voice on the development team is not enough; expert domain knowledge is often tacit [35]. We had four workplace experts on our development team and still found a wealth of new information via direct observation of classroom activity. We were able to quickly identify fundamental domain categories and distinctions, physical constraints, and practices. These helped us interrogate and develop our vision, and in turn guided subsequent requirements development activities.

The trade-off analysis we produced a form of design rationale—a claims analysis that identified potential causal relationships between desirable or undesirable consequences for users and specific features of classroom scenarios [12], [18]. More generally, design rationale is documentation of discussions, debates and negotiations that determined a design, reasons for particular features, reasons against features not included, etc. [27]. The analysis of the trade-offs implicit in a set of observed workplace scenarios can facilitate the integration (in the sense of coercing) the team's initial vision into work practices, on the one hand, and projecting more detailed design scenarios, on the other.

We draw analogy between the classroom activity design in our case study and what might be called COTS (Commercial Off-The-Shelf) prototyping. We envisioned and crudely prototyped classroom scenarios in order to better understand the design space of activities and technologies with which we were working. Recruiting existing technology allowed us to progress more rapidly, and to keep our focus on requirements development, not specification and implementation. This approach is general; a great variety of software applications and components are available as shareware, demoware, and inexpensive packages. The experience we gathered from working with a set of computer-mediated communication mechanisms in our activity prototypes was very valuable in highlighting specific needs and opportunities for the technology-in-use.

Virtual Laboratory Case Study	General Requirements Development
Project Vision Development: analysis of educational technology research and public policy statement; development of touchstone Marissa scenario	Project Charter: initial statement of work obtained from (or created for) customer or from market analysis; development of initial system envisionment scenario
Classroom Activity Observation: sustained ethnographic study of classrooms; inventory extant classroom scenarios; understand classroom categories, distinction and preferences	Workplace Ethnography: sustained observational study of target usage context; inventory of extant workplace scenarios, and categories, distinctions, and preference in current workplace practices
Classroom Activity Analysis: trade-off analysis of classroom scenarios; consider possible desirable and undesirable consequences of specific features of observed activities	Design Rationale: trade-off analysis of features identified in workplace ethnography; requirements derived through understanding the desirable and undesirable consequences of specific features
Classroom Activity Design: envision and crudely prototype classroom activity scenarios to better understand usage implications of computer-mediated communications technology	Commercial Off-The Shelf (COTS) Prototype: early designs of new work activities; scenarios are developed to integrate initial vision, trade-off analysis and technology possibilities
School Pragmatics: formative evaluation of crudely prototyped classroom activities brings to light school organizational and operational factors	External Factors: formative evaluation of prototyped activities; new usage situations bring to light issues concerning workplace pragmatics

Fig. 14. Generalizing five stages of requirements development.

Our fifth stage of requirements development was school pragmatics, the formative, or design-oriented, evaluation of prototyped classroom activities.

In our case study, this brought to light significant contextual factors which could not be anticipated—they emerge from the interaction of the technology and the usage situation. Powerful external factors always impinge on the practical efficacy of designs; for example, the use of video conferencing was constrained by features of class scheduling that seemed trivial in the abstract. Formative evaluation is the only way to identify and manage such emergent external factors.

In this case study, we set out to investigate an extended sociotechnical development process. We wanted to generalize a scenario-based HCI design method to a software development problem involving a diversity of stakeholders, physical constraints, organizational complexity, and a distinctive workplace culture. We pursued a differentiated set of requirements development activities, which brought to light a variety of requirements including workplace practice requirements. We have proposed a generalization of this process in Fig. 14. Each of the requirements development activities of the process template has an independent utility; each already occurs in contemporary system development practice. We are proposing that the ensemble of these activities, unified through the common vocabulary of scenarios and shared among the stakeholders in a development project, attains a synergy with respect to requirements development.

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REFERENCES

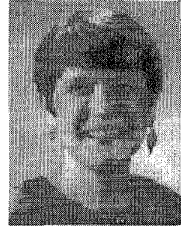
- [1] American Association for the Advancement of Science, *Science Assessment in the Service of Reform*. Washington, D.C.: AAAS, 1991.
- [2] R.K.E. Bellamy and J.M. Carroll, "Structuring the Programmer's Task," *Int'l J. Man-Machine Studies*, vol. 37, no. 4, pp. 503-527, 1992.
- [3] F.P. Brooks, *The Mythical Man-Month: Essays on Software Engineering*. anniversary edition, Reading, Mass.: Addison-Wesley, 1995.
- [4] J.M. Carroll, "The Scenario Perspective on System Development," *Scenario-Based Design: Envisioning Work and Technology in System Development*, J.M. Carroll, ed., pp. 1-17. New York: John Wiley & Sons, 1995.
- [5] J.M. Carroll, "Becoming Social: Expanding Scenario-Based Approaches in HCI," *Behaviour and Information Technology*, vol. 15, no. 4, pp. 266-275, 1996.
- [6] J.M. Carroll, "Scenario-Based Design," *Handbook of Human-Computer Interaction*, second edition, M. Helander and T.K. Landauer, eds., pp. 383-406, Amsterdam: North Holland, 1997.
- [7] J.M. Carroll and R.L. Campbell, "Artifacts as Psychological Theories: The Case of Human-Computer Interaction," *Behaviour and Information Technology*, vol. 8, pp. 247-256, 1989.
- [8] J.M. Carroll, W.A. Kellogg, and M.B. Rosson, "The Task-Artifact Cycle," *Designing Interaction: Psychology at the Human-Computer Interface*, J.M. Carroll, ed., pp. 74-102, New York: Cambridge Univ. Press, 1991.
- [9] J.M. Carroll and M.B. Rosson, "Human-Computer Interaction Scenarios as a Design Representation," *Proc. 23rd Hawaii Int'l Conf. System Sciences, Software Track*, pp. 555-561, B.D. Shriver, ed. Los Alamitos, Calif.: IEEE CS Press, 1990.
- [10] J.M. Carroll and M.B. Rosson, "Deliberated Evolution: Stalking the View Matcher in Design Space," *Human-Computer Interaction*, vol. 6, pp. 281-318, 1991.
- [11] J.M. Carroll and M.B. Rosson, "Managing Evaluation Goals for Training," *Comm. ACM*, vol. 38, no. 7, pp. 40-48, 1995.
- [12] J.M. Carroll and M.B. Rosson, "Getting Around the Task-Artifact Cycle: How to Make Claims and Design by Scenario," *ACM Trans. Information Systems*, vol. 10, pp. 181-212, 1992.
- [13] J.M. Carroll and M.B. Rosson, "Developing the Blacksburg Electronic Village," *Comm. ACM*, vol. 39, no. 12, pp. 69-74, 1996.
- [14] J.M. Carroll, M.B. Rosson, G. Chin, and J. Koenemann, "Requirements Development: Stages of Opportunity for Collaborative Needs Discovery," *Proc. Second Int'l ACM Symp. Designing Interactive Systems (DIS'97)*, pp. 55-64, Amsterdam: The Netherlands, Aug. 1997.
- [15] J.M. Carroll, M.K. Singley, and M.B. Rosson, "Integrating Theory Development with Design Evaluation," *Behaviour and Information Technology*, vol. 11, pp. 247-255, 1992.
- [16] P.B. Checkland, *Systems Thinking, Systems Practice*. Chichester, United Kingdom: John Wiley & Sons, 1981.
- [17] G. Chin, "A Methodology for Integrating Ethnography, Scenarios, and Participatory Design," PhD dissertation, Computer Science Dept., Virginia Tech, Blacksburg, Va., 1999.
- [18] G. Chin, M.B. Rosson, and J.M. Carroll, "Participatory Analysis: Shared Development of Requirements from Scenarios," *Proc. ACM Conf. Human Factors in Computing Systems (CHI'97)*, pp. 162-169, Atlanta, Mar. 1997.
- [19] L. Erskine, D. Carter-Todd, and J. Burton, "Dialogical Techniques for the Design of Web Sites," *Int'l J. Human-Computer Studies*, vol. 47, pp. 169-195, 1997.
- [20] D. Fetterman, *Ethnography: Step by Step*. Newbury Park, Calif.: Sage, 1989.
- [21] J. Greenbaum and M. Kyng, *Design at Work: Cooperative Design of Computer Systems*. Hillsdale, N.J.: Erlbaum, 1991.
- [22] I. Jacobson, "The Use-Case Construct in Object-Oriented Software Engineering," *Scenario-Based Design: Envisioning Work and Technology in System Development*, J.M. Carroll, ed., pp. 309-336, New York: John Wiley & Sons, 1995.
- [23] J. Koenemann, J.M. Carroll, M. Abrams, M.B. Rosson, and C.A. Shaffer, "Designing Collaborative Applications for Classroom Use: The LiNC Project," *The Design of Children's Technology*, A. Druin, ed. San Francisco: Morgan-Kaufmann, pp. 99-123, 1998.
- [24] M. Kyng, "Creating Contexts for Design," *Scenario-Based Design: Envisioning Work and Technology in System Development*, J.M. Carroll, ed., pp. 85-107, New York: John Wiley & Sons, 1995.
- [25] S. Laughton, "The Design and Use of Internet-Mediated Communication Applications in Education: An Ethnographic Study," PhD dissertation, Computer Science Dept., Virginia Tech, Blacksburg, Va., 1996.
- [26] Montgomery County Public Schools, Six-Year Technology Plan for Montgomery County Public Schools, 1994. (<http://www.bev.net/education/schools/admin/techplan.html>)
- [27] T.P. Moran and J.M. Carroll, *Design Rationale: Concepts, Techniques and Use*. Mahwah, N.J.: Erlbaum, 1996.
- [28] National Science Teachers Association, *Scope, Sequence, and Coordination of Secondary School Science*. Washington, D.C.: NSTA, 1990.
- [29] J. Piaget and B. Inhelder, *The Psychology of the Child*. New York: Basic Books, 1969.
- [30] M.B. Rosson and J.M. Carroll, "Narrowing the Specification-Implementation Gap in Scenario-Based Design," *Scenario-Based Design: Envisioning Work and Technology in System Development*, pp. 247-278, J.M. Carroll, ed. New York: John Wiley & Sons, 1995.
- [31] J. Sanders and E. Curran, *Software Quality: A Framework for Success in Software Development and Support*. Reading, Mass.: Addison-Wesley, 1994.

- [32] M.K. Singley and J.M. Carroll, "Synthesis by Analysis: Five Modes of Reasoning that Guide Design," *Design Rationale: Concepts, Techniques, and Use*, pp. 241-265, T.P. Moran and J.M. Carroll, eds. Mahwah, N.J.: Lawrence Erlbaum Assoc., 1996.
- [33] R.B. Smith, "The Alternate Reality Kit: An Example of the Tension Between Literalism and Magic," *Proc. ACM Conf. Human Factors in Computing Systems and Graphical Interfaces (CHI+GI'87)*, pp. 61-67, Toronto, Apr. 1987.
- [34] L. Sproull and S. Kiesler, *Connections: New Ways of Working in the Networked Organization*. Cambridge, Mass.: MIT Press, 1991.
- [35] L. Suchman, "Making Work Visible," *Comm. ACM*, vol. 38, no. 9, pp. 56-65, 1995.
- [36] A.G. Sutcliffe and J.M. Carroll, "Generalising Claims and the Resue of HCI Knowledge," *People and Computers XIII: Proc. HIC '98*, British Computer Society's Human-Computer Interaction '98 Conf., Sheffield, H. Johnson, L.M. Nigay, and C.R. Roas, eds., London: Springer-Verlag, Sept. 1998.
- [37] "Making Claims on Domains," *Proc. of British Computing Society Human-Computer Interaction '98 Conf.*, 1998.
- [38] D. Tyack and L. Cuban, *Tinkering Toward Utopia: A Century of Public School Reform*. Boston: Harvard Univ. Press, 1995.
- [39] L.S. Vygotsky, *Mind in Society*. Cambridge: Harvard Univ. Press, 1978.
- [40] R. Wirfs-Brock, "Designing Objects and Their Interactions: A Brief Look at Responsibility-Driven Design," *Scenario-Based Design: Envisioning Work and Technology in System Development*, pp. 337-360, J.M. Carroll, ed. New York: John Wiley & Sons, 1995.
- [41] M. Williams, "Enabling Schoolteachers to Participate in the Design of Educational Software," *Proc. Participatory Design Conf. (PDC'94)*, pp. 153-157, 1994.
- [42] P. Zave and M. Jackson, "Four Dark Corners of Requirements Engineering," *ACM Trans. Software Eng. and Methodology*, vol. 6, no. 1, pp. 1-30, Jan. 1997.



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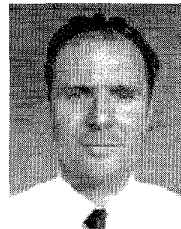
Wiley & Sons, 1995) and *Design Rationale: Concepts, Techniques and Use* (with T.P. Moran, Erlbaum, 1996). In 1994, he won the Rigo Career Award from ACM SIGDOC for contributions stemming from an earlier book, *The Nurnberg Funnel: Designing Minimalist Instruction for Practical Computer Skill* (MIT Press, 1990).



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