Chapter 1
Introduction: What Are Intelligent Tutoring Systems, and Why This Book?

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Abstract. This introductory chapter opens the doors to the field of Intelligent Tutoring Systems (ITS) and ITS research. A historical perspective provides insight into the genesis of the field, which is a prerequisite for understanding the recent advances presented in the book. Challenges specific to the field are introduced, and the community and its dynamics are described. The chapter ends with a presentation of the book's contents and organization.

1.1 Why This book?

The idea for this book on Intelligent Tutoring Systems (ITS) was sparked by the success of the ITS'08 international conference. The number of presentations and their quality bore witness to the vitality and maturity of the field, and the enthusiasm of the participants held out a promise of sustainability and innovative research. Long life to ITS research!

"Not ANOTHER book on ITS!" Actually, this field is not as rich in books as it is in journals and conference proceedings. The first, simply entitled Intelligent Tutoring Systems, was edited by Sleeman and Brown (1982), who coined the term. It was soon followed by Wenger's Artificial Intelligence and Tutoring Systems (1987), which established what would become the so-called "traditional ITS architecture" with its four components: domain, student, tutor and user interface. Recently, Woolf's book *Building Intelligent Interactive Tutors* (2008) offered an authoritative encyclopedia for anyone desiring an initiation into ITS building.

So why have we written this book, and for whom? Our intention is twofold: to provide a basic understanding of the field and its evolution, and to highlight recent advances and work in progress. Novices and experts alike should find it useful; at least that is our hope. Our intention is to reach two main categories of readers: ITS experts and experts-to-be (graduate students); and non-experts who want to gain

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some understanding of the main ideas and facts in the field of ITS. The book is divided into five parts. The introductory chapters to these parts, which summarize foundations, developments, strengths and weaknesses in each of the areas covered, are addressed to all readers. For those who want more in-depth knowledge, we give the floor to researchers who present their work, their results, and their view of what the future holds. It is our hope that all readers will find the book informative and thought-provoking.

The next sections contain a summary of the origin of ITS, its foundations and goals, its architecture, its success stories and challenges, the people who have been contributing to the field, and the community that has formed over the years, in a close relationship with the Artificial Intelligence and Education (AIED) Society. The chapter ends with a presentation of the book's contents and organization.

1.2 Intelligent Tutoring Systems and Their Architecture

All ITSs share the same goal: to provide tutorial services that support learning. That being said, they show a vast variety of ways to conceptualize, design and develop these services. Efforts in this direction first began in the 1960s and '70s, with the development of what was called Intelligent Computer-Assisted Learning (ICAI) by Carbonell (1970). The term "Intelligent Tutoring Systems" was coined by Sleeman and Brown in their volume of the same title (1982). The first ITS conference (1988) provided an opportunity to share and consolidate ideas, and it evolved into a biannual conference with full proceedings. Several research labs would dedicate their work to ITS, raising considerable funds and deploying their systems in real settings. These achievements are summarized in the following section.

1.2.1 A Growing Field

In 1990, 20 years after its birth, the field had passed its infancy and could reflect on the first generation of contributions, as evidenced by two publications that appeared in that year: an overview of the field (Nwana 1990) and a position paper (Self 1990). In 2008-2009, a generation later, further evolution is described in two volumes: one that reflects the latest developments (Woolf et al. 2008) and one that provides a broad, in-depth survey of the ITS field (Woolf, 2008). These landmark publications will guide our description of a field that has been growing for three generations.

To understand the first generation, from 1970 to 1990, it is essential to be aware of the climate of the time and the motivations underlying the field's emergence. Artificial Intelligence (AI) was in full bloom and seeking applications for its advanced techniques in both computer and cognitive science. Computer-Assisted Instruction (CAI) was a mature and promising technology with a target market. The educational system was looking for solutions to overcome its limitations in order to deal with large groups in schools. Visionary scientists and pioneers imagined that merging AI with CAI could yield solutions to improve school instruction (Carbonell 1970). In 1984, Bloom published an article demonstrating that individual tutoring is twice as effective as group teaching. AI researchers saw a solid foundation upon which they could create intelligent systems that would provide effective tutoring for every student, tailored to her needs and pace of learning. Nwana has reviewed the systems produced by this generation and counted 43 (Nwana 1990). The dream at that time was that children would "have access to what Philip of Macedon's son had as royal prerogative: the personal services of a tutor as well informed as Aristotle" (Suppes, quoted in Nwana 1990).

In 1990, Self published an article in the first volume of the *Journal of Artificial Intelligence in Education (AIED)*, after a provocative talk at the 4th International Conference on Artificial Intelligence in Education, in which he called for theoretical foundations for ITS (Self 1990). In his article, Self (who was to become the first president of the AIED Society in 1993) claimed that in order to attain the status of a scientific field, ITS research needs scientific foundations. In his view, pursuing the goal of *ITS as human teacher* was overstretching an analogy and taking a wrong direction. He suggested viewing ITS as an engineering design field, which should equip itself with the theories, methods and techniques appropriate for a design field.

Some twenty years later, the field of ITS shows signs of vitality and self-confidence. Has it answered Self's call? There can be no doubt that it has. The AIED journal, the biannual AIED conference and the now biannual ITS conference all feature high-level theoretical and technical papers, presenting implementations in schools and other settings, and bold, innovative developments (Woolf et al. 2008; Woolf 2008). These results are reflected in the chapters of this book.

1.2.2 ITS Architectures

Why should architecture be a central issue? In 1990, talking of the three-component architecture (domain, student, tutoring), Self wrote: "an unquestioning adoption of the traditional trinity model will cause problems in ITS implementation and will restrict the scope of ITS research . . . the main concern is that the traditional trinity imposes a philosophy which is not an appropriate basis from which to develop a theory of ITS" (Self 1990). This criticism warrants special attention. What Self called the trinity is also known as the four-component architecture, where the fourth element is the user interface (Fig. 1.1).

What is the semantics of this architecture? Basically, it divides the system into four components where knowledge and reasoning are needed, leaving the integration problem open. In actuality, the systems generally show an emphasis (in both computational and control terms) on one component over the others. What can we expect to find in each component?

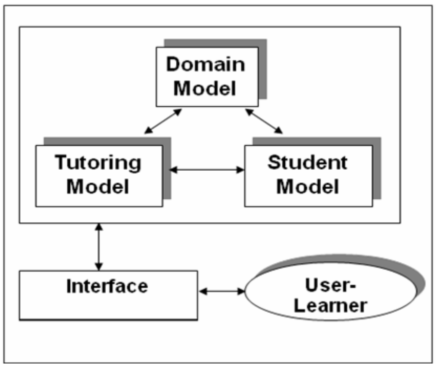

Fig. 1.1 The four-component architecture

The ***domain model*** (also called expert knowledge) contains the concepts, rules, and problem-solving strategies of the domain to be learned. It can fulfill several roles: as a source of expert knowledge, a standard for evaluating the student's performance or for detecting errors, etc. It is sometimes organized into a curriculum, a structure including all the knowledge elements linked together according to pedagogical sequences. Each knowledge unit can be more or less detailed and the curriculum can be practically organized in a dynamic model, according to various structures such as hierarchies, semantic networks, frames, ontology and production rules. The crucial problems concern the capability to reason with the model and gradually adapt the explanation of the reasoning to the learner.

The ***student model* is** the core component of an ITS. Ideally, it should contain as much knowledge as possible about the student's cognitive and affective states and their evolution as the learning process advances. The student model is usually viewed as a dynamic model that implements several functions. Wenger (1987) assigned three main functions to the student model: 1) it must gather explicit and implicit (inferred) data from and about the learner; 2) it must use these data to create a representation of the student's knowledge and learning process; and 3) it must account for the data by performing some type of diagnosis, both of the state of the student's knowledge and in terms of selecting optimal pedagogical strategies for presenting subsequent domain information to the student. In the same vein, Self (1988) identified six major roles for the student model: 1) Corrective: to help eradicate bugs in the student's knowledge; 2) Elaborative: to help correct 'incomplete' student knowledge; 3) Strategic: to help initiate significant changes in the tutorial strategy other than the tactical decisions of 1 and 2 above; 3) Diagnostic: to help diagnose bugs in the student's knowledge; 5) Predictive: to help determine the student's likely response to tutorial actions; 6) Evaluative: to help assess the student or the ITS. These functions and roles have been both expanded and diversified in the years since then.

The ***tutoring model*** receives input from the domain and student models and makes decisions about tutoring strategies and actions. Based on principled knowledge, it must make such decisions as whether or not to intervene, and if so, when and how. Content and delivery planning are also part of the tutoring model's functions.

Tutoring decisions would ideally be reflected in different forms of interaction with the student: socratic dialogs, hints, feedback from the system, etc. More generally, student/tutor interactions usually occur through the learning interface, also known as the communication or ***interface component***. This component gives access to the domain knowledge elements through multiple forms of learning environment, including simulations, hypermedia, micro-worlds, etc.

In his survey paper, Nwana reviewed other architectures that have been proposed or adopted (1990). In his discussion, he underlines the strong link between architecture and paradigm (what he calls a philosophy) and explains that differing tutoring philosophies emphasize different components of the learning process: domain, student or tutor. The architectural design of an ITS reflects this emphasis, and this leads to a variety of architectures, none of which, individually, can support all tutoring strategies (Nwana 1990).

Twenty years later, research teams report a wide range of architectures, and they may be unaware of this link with a paradigm, or claim that there is no explicit link. The themes selected for special issues of the *AIED* journal or for categories in the ITS and AIED conferences indicate a wide spectrum of topics, and architecture is not a main concern (Woolf et al. 2008; Woolf 2008). The present book addresses most of these topics and integrates them in the introductory chapter of each part.

One important aspect is that, beside this classic component view of ITSs, these systems offer a number of services. The implementation of some of these services usually transcends the individual components. For instance, the diagnostic service is sometimes considered to be part of the student model, but many other researchers see it as a function of the tutor component.

In the research perspective, a number of advanced ideas and techniques have been explored (open learner model, virtual reality agents, machine learning techniques, data mining techniques, etc.) and will be presented in the chapters of this book.

1.3 ITS and AIED: The Boundaries and the Community

ITS and AIED have developed simultaneously as two complementary fields involving what is in fact one large community. The term ITS is more restrictive than AIED, but the field is inclusive, and open to all AIED-related themes. ITS conferences are organized every other year, alternating with the AIED conference. Both publish their proceedings, and the AIED community is organized as a society, with its journal. Does AIED offer a choice venue for reflection about ITS research? The answer is yes, but reflection and discussions also occur at ITS events. A common topic of discussion is the high level of difficulty of ITS in design and computational terms.

ITS research is an interdisciplinary field, welcoming people from various disciplines, including computer science, psychology, the learning sciences and instructional technology, among others. This interdisciplinarity is both a challenge and a richness. Many ITS researchers study both computer science and cognitive science in order to achieve deep integration. Some have difficulty bridging the gap between bodies of knowledge and cultures from two or more disciplines; others prefer not to address the problem. Some stay and some leave; that's life! C'est la vie!

The future will see the field of ITS continue to embrace new technologies and adapt itself to new generations of researchers and graduate students. ITS will continue to spawn new domains, as it has the fields of qualitative reasoning, hypermedia systems, and educational data mining.

1.4 Organization and Content of This Book

In its structure, this book follows the traditional component architecture, for a shared understanding of the ITS domain. It is composed of five parts. The first three deal with modeling the domain, the tutor and the student, respectively, and the fourth looks at ITS construction. Each of these four parts begins with an introductory chapter that provides an overview of the issue, followed by a number of chapters that deal with specific approaches for dealing with that issue. The last part covers topics related to social, cultural and privacy issues.

1.4.1 Part 1: Modeling the Domain

Part 1 looks at how domain knowledge is represented in ITS. There are five chapters in this part.

Chapter 2, by Nkambou, presents an overview of domain acquisition issues in ITS since the field's emergence. The acquisition and representation of a domain knowledge model is a difficult problem that has been the subject of numerous research efforts in both the AI and AIED fields. The chapter surveys the methods and techniques used for this purpose. It begins by presenting and discussing the epistemological issue associated with domain knowledge engineering. Several knowledge representation languages are then briefly presented, considering their expressiveness, inferential power, cognitive plausibility and pedagogical emphasis. The chapter ends by establishing links with the subsequent chapters in this part of the book.

Chapter 3, by Aleven et al., is about rule-based cognitive modeling for ITS. Rule-based cognitive models play many roles in ITS development. They help in understanding student thinking and problem solving, guide many aspects of the tutor design, and can function as the "smarts" of the system. ITSs using rule-based cognitive models have been demonstrated to be successful in improving student learning in a range of learning domains. A rule-based model used in the Geometry Cognitive Tutor illustrates how, when modeling novice problem-solving knowledge in a complex domain, cognitive fidelity and ease of engineering are two important concerns shaping a model. More recently, rule-based modeling has been used effectively to provide tutoring at the metacognitive level. Much on-going work is aimed at making models easier to develop: for example, by creating efficient and effective authoring tools, or by using machine learning to infer models from author-provided examples or student log data.

Chapter 4, by Mitrovic, describes the constraint-based modeling approach. Stellan Ohlsson proposed constraint-based modeling (CBM) in 1992 as a way to overcome some problems in student modeling. Since then, the approach has been extended and used in numerous intelligent tutoring systems, which authors refer to as constraint-based tutors. CBM is now an established methodology for modeling instructional domains and for representing students' domain knowledge and higher-level skills. Authoring support for constraint-based tutors is now available, as well as mature, well-tested deployment environments. The chapter presents CBM, its foundations and extensions, and various types of instructional domains it has been applied to, and concludes with avenues for future research.

Chapter 5, by Founier-Viger et al., presents methods for coping with what have been termed "ill-defined domains": domains where classical approaches for building tutoring systems are not applicable or do not work well. The chapter provides an updated overview of the problem, and solutions for building intelligent tutoring systems for these domains. In its presentation, it considers three complementary and important perspectives: the characteristics of ill-defined domains, the approaches for supporting tutoring services in these domains, and suitable teaching models. Throughout the chapter, numerous examples are given to illustrate the discussion.

Part 1 ends with Chapter 6, by Zouaq and Nkambou, which gives more details about the ontology-based approach to domain modeling. With the advent of the Semantic Web, the field of domain ontology engineering has gained increasingly in importance. This innovative field may have a big impact on computer-based education and will certainly contribute to its development. The chapter presents a survey on domain ontology engineering and, especially, domain ontology learning, with a particular focus on automatic methods for ontology learning. After summarizing the state of the art in natural language processing techniques and statistical and machine learning techniques for ontology extraction, the chapter explains how intelligent tutoring systems may benefit from this engineering, and talks about the challenges the field is facing.

1.4.2 Part 2: Modeling the Tutor

Part 2 describes tutor modeling approaches and different ways learning environments behave.

Chapter 7, by Bourdeau and Grandbastien, is the introductory chapter for this part. It provides the reader with an overview of tutor modeling in ITS research. Starting with the origin of tutor modeling and a characterization of the tutoring process, it proposes a general definition of tutoring and a description of tutoring functions, variables, and interactions. The Interaction Hypothesis is presented and discussed. This discussion of tutor modeling is followed by the development of the tutorial component of an ITS, and its evaluation. New challenges, such as integrating the emotional states of the learner, are described, and perspectives for opening up the tutor model or providing it with social intelligence are presented.

In Chapter 8, Dubois et al. offer a thorough analysis of the way tutoring decisions are made in cognitive tutors. The chapter describes how AI techniques are utilized in artificial tutoring systems to reach decisions on when and how to intervene. Particular attention is given to the path of "natural" AI for tutoring systems, using human cognition as a model for artificial general intelligence. One tutoring agent built over a cognitive architecture, Conscious Tutoring System (CTS), illustrates this direction. The chapter concludes with a brief look at what may be the future for artificial tutoring systems: biologically-inspired cognitive architectures.

In Chapter 9, Olney, Graesser and Person present their work on conversational interaction in human tutoring and their attempts to build intelligent tutoring systems to simulate this interaction. They address the strategies, actions and dialogue of novice tutors and describe how novice tutoring has been implemented in an ITS called Autotutor, with learning gains comparable to those seen with novice human tutors. They also describe how they have recently extended their investigation to highly accomplished expert human tutors. Their goal is to understand what it is about accomplished, expert human tutors that produces outstanding learning gains. The chapter elaborates on the contrast between novice and expert, both in terms of human tutoring and in the ITS components required to mimic the interaction of novice and expert human tutors.

Chapter 10, by Woolf, describes the automatic recognition of and response to human emotion found in intelligent tutors. The chapter describes how tutors can recognize student emotion with more than 80% accuracy relative to student self-reports, using wireless sensors that provide data about posture, movement, grip tension, facially expressed mental states and arousal. Pedagogical agents have been used that provide emotional or motivational feedback. Students using such agents increase their math value and show improved self-concept and mastery orientation, with females reporting more confidence and less frustration. Low-achieving students—one-third of whom have learning disabilities—report higher affective needs than their higher-achieving peers. After interacting with affective pedagogical agents, low-achieving students improve their affective outcomes and report reduced frustration and anxiety.

Chapter 11, by Mizoguchi et al., is about the use of ontology in modeling the tutoring process. The chapter calls for the extensive modeling of tutoring knowledge by providing in-depth declarative knowledge and higher-level reasoning capabilities. It describes the achievements of a ten-year research project aimed at developing an ontology of education (OMNIBUS), which offers a common framework to be shared by all ITSs, regardless of paradigm or technology. It also describes some recent advances in ontology-based learning design (SMARTIES), and provides access to educational strategies inspired by educational theories or practice.

This part ends with Chapter 12, by vanJoolingen et al., which presents an approach for modeling knowledge in simulation-based inquiry learning. The approach requires a model of the domain that is executable, as well as a model of the learners' knowledge about the domain. An intermediate level is formed by models of the domain that are created by students, as is done in modeling environments. An approach is presented for generating student-created models from drawings.

This approach requires drawing segmentation, shape recognition and model generation, which are performed based on density-based clustering and elementary shape recognition combined with a shape ontology and model fragment composition, respectively. The final result is an executable model that can be used to generate simulation outcomes based on learners' conceptions. The role of such a system is discussed, especially with respect to the diagnosis of misconceptions and the generation of tutoring interventions based on confronting learners with the consequences of their conceptions.

1.4.3 Part 3: Modeling the Student

This part presents an overview of techniques used for student modeling. Specific emphasis is given to some important approaches for building the student model: the data mining approach, the open learner modeling approach and the Bayesian network approach.

Chapter 13, by Woolf, is the introductory chapter of this part. It describes how to build student models for intelligent tutors and indicates how knowledge is represented, updated, and used to improve tutor performance. It provides examples of how to represent domain content and describes evaluation methodologies. Several future scenarios for student models are discussed, including using the student model: 1) to support assessment for both formative issues (the degree to which the student has learned how to learn – for the purpose of improving learning capacity and effectiveness) and summative considerations (what is learned – for purposes of accountability and promotion); 2) to track when and how skills were learned and what pedagogies worked best for each learner; and 3) to include information on the cultural preferences of learners and their personal interests, learning goals, and personal characteristics. Ultimately, student model servers will separate student models from tutors and will be a part of wide area networks, serving more than one application instance at a time.

Chapter 14, by Conati, presents some techniques and issues involved in building probabilistic student models based on Bayesian networks and their extensions. It describes the pros and cons of this approach, and presents examples from two existing systems: an ITS (Andes) and an educational game (PrimeClimb).

Chapter 15, by Bull and Kay, describes the range of purposes that open learner models can serve, illustrating these with diverse examples of the ways they have been made available in several research systems. This is followed by discussion of the closely related issues of openness and learner control and approaches that have been explored for supporting learning by making the learner model available to people other than the learner. The chapter provides a foundation for understanding the range of ways in which open learner models have already been used to support learning, as well as directions yet to be explored.

In Chapter 16, Baker summarizes key data-mining methods that have supported student-modeling efforts, also discussing the specific constructs that have been modeled with the use of educational data mining. He also discusses the relative advantages of educational data mining compared to knowledge engineering, and key directions in which research is needed in order for educational data-mining research to reach its full potential.

This part ends with Chapter 17, by Frasson and Chalfoun. They point out the role of emotions in learning, discussing the different types and models of emotions that have been considered to date. They also address an important issue concerning the different means used to detect emotions. They describe recent approaches which measure brain activity using the electroencephalogram (EEG) in order to determine the learner's mental state, how long this state can exist, and what event can change it. The authors also present the main components of an emotionally intelligent tutoring system capable of recognizing, interpreting and influencing someone's emotions. In conclusion, they look at future perspectives and new directions in the area of emotional learning.

1.4.4 Part 4: Building Intelligent Tutoring Systems

In this part of the book, the issue of building tutoring systems is examined and possible solutions are discussed. A sample ITS is described to give the reader a close-up of how ITSs are used in real life.

Chapter 18, by Nkambou, Bourdeau and Psyché, is the introductory chapter to this part, and provides an overview of methods and tools for building ITSs. In this chapter, the challenge of building or authoring an ITS is addressed, along with problems that have arisen and been dealt with, solutions that have been tested, and evaluation methodologies. The chapter begins by clarifying what is involved in building an ITS. It then positions this challenge in the context of ITS research. The authors conclude with a series of open questions, and an introduction to the other chapters in this part of the book.

Chapter 19, by Paquette et al., presents the ASTUS authoring tool and evaluates its strengths and weaknesses compared to the well-known Cognitive Tutors Authoring Tools (CTAT). In the context of a multi-column subtraction problem, the chapter compares the two tools' ability to handle a comprehensive model of a well-defined domain. The model integrates various known procedural errors taken from the literature to see how each framework deals with complex situations where remedial help is needed. Examples of such situations include handling ambiguous steps, deducing errors from multiple steps, giving pedagogical feedback on composite errors, recognizing off-path steps and producing rich feedback on the tutor's interface. Selected scenarios in the subtraction domain are presented to illustrate that ASTUS can display more sophisticated behavior in these situations than CTAT. ASTUS achieves this by relying on an examinable hierarchical knowledge representation system and a domain-independent MVC-based approach to build the tutor's interface.

Chapter 20, by Razzaq and Heffernan, presents ASSISTment, an open content authoring tool. The difficulty of designing, conducting, and analyzing experiments means that there is often a dearth of empirical data to support or refute ideas. Designing and conducting a simple randomized controlled experiment to compare two different ways of teaching requires a great deal of effort by a teacher or a researcher. The difficulty of conducting such experiments, and then later analyzing the results, may be why so few randomized, controlled experiments are conducted in education. One of the goals of the ASSISTment System is to alleviate some of these difficulties. The chapter describes web-based tools that allow researchers to easily design, build and compare different ways to teach children. These tools can administer randomized controlled experiments to large numbers of students.

Chapter 21, by VanLehn et al., presents one of the most popular ITSs: Andes. The Andes physics tutoring system demonstrates that student learning can be significantly increased merely by upgrading the homework problem-solving support. Five years of experimentation at the United States Naval Academy indicates that Andes significantly improves student learning compared to doing the same homework with paper and pencil. Andes' key feature appears to be the grain size of interaction. The chapter describes Andes' behavior, the system design and implementation, evaluations of pedagogical effectiveness, and recent progress on dissemination/scale-up.

1.4.5 Part 5: Social, Cultural and Privacy Issues

This part presents some important issues currently surfacing in the ITS community. In Chapter 22, Tchounikine, Rummel and McLaren discuss how recent advances in the field of computer-supported collaborative learning (CSCL) have created the opportunity for new synergies between CSCL and ITS research. Three "hot" CSCL research topics are used as examples: analyzing individual and group interactions, providing students with adaptive intelligent support, and providing students with adaptive technological means.

Chapter 23, by Aimeur and Hage, is about privacy issues. The chapter describes the security and privacy-protection approaches taken by ITS and e-learning systems generally, and discusses the challenges they still face, as well as the particular challenges raised by Web 2.0.

The last chapter in the book, Chapter 24, by Blanchard and Ogan, deals with cultural issues. It examines what it means to adapt intelligent tutoring systems for users with diverse cultural backgrounds, and how intelligent tutoring systems can be used to support instruction that takes culture into consideration. The authors discuss the major research issues involved in modifying ITS to support these efforts. To provide insight into the current landscape of the field, they briefly outline some recent research achievements and highlight significant current and future issues raised by the integration of cultural concerns and educational technology.

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