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Robert J. Mislevy, John T. Behrens,
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Editor: Michael Russell
russelmh@bc.edu
Technology and Assessment Study Collaborative
Lynch School of Education, Boston College
Chestnut Hill, MA 02467

Copy Editor: Jennifer Higgins
Design: Thomas Hoffmann
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Abstract:

People use external knowledge representations (KRs) to create, identify, depict, transform, store, share, and archive information. Learning to work with KRs is central to becoming proficient in virtually every discipline. As such, KRs play central roles in curriculum, instruction, and assessment. We describe five key roles of KRs in assessment:

1. An assessment is itself a KR, which makes explicit the knowledge that is valued, ways it is used, and standards of good work.
2. The analysis of any domain in which learning is to be assessed must include the identification and analysis of the KRs in that domain.
3. Assessment tasks can be structured around the knowledge, relationships, and uses of domain KRs.
4. "Design KRs" can be created to organize knowledge about a domain in forms that support the design of assessment.
5. KRs in the discipline of assessment design can guide and structure domain analyses (re #2), task construction (re #3), and the creation and use of design KRs (re #4).

The third and fourth roles are developed in greater detail, through an "evidence-centered" design perspective that reflects the fifth role. Recurring implications of technology that leverage the impact of KRs in assessment are highlighted, including task design supports and automated task construction and scoring. Ideas are illustrated with "generate examples" tasks and simulation tasks for computer network design and troubleshooting.

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On the Roles of External Knowledge Representations in Assessment Design

Robert J. Mislevy
Daisy Wise Rutstein
Fielding I. Winters
University of Maryland, College Park
John T. Behrens
Sarah F. Demark
Dennis C. Frezzo
Ken Stanley
Cisco Systems, Inc.
Randy E. Bennett
Educational Testing Service
Roy Levy
Arizona State University
Daniel H. Robinson
University of Texas at Austin
Valerie J. Shute
Florida State University

Introduction

Knowledge representation is a central theme in cognitive psychology. Internal knowledge representation refers to the way that information about the world is represented in our brains, and as such lies at the center of learning, interacting, and problem-solving of all kinds. This paper concerns external forms of knowledge representation. An external knowledge representation (abbreviated KR below), or inscription (Lehrer & Schauble, 2002), is a physical or conceptual structure that depicts entities and relationships in some domain, in a way that can be shared among different individuals or the same individual at different points in time. KRs are human inventions that overcome obstacles to human information processing with respect to working memory limitations, faulty long-term memory over time and in volume, coordinating actions across individuals, and providing common ways of thinking about some phenomenon of shared interest. Examples of KRs include maps, lists, graphs, wiring diagrams, bus schedules, musical notation, mathematical formulas, object models for business systems, and the 7-layer OSI model for computer networks.

This paper considers the roles of KRs in educational assessment, with an eye toward making the activities of assessment design more explicit, more valid, and more efficient. A red thread highlighting the implications of technology runs through the discussion. Technological developments make KRs possible that are more interactive, support automated transformations, and enable collaboration in ways that are transforming the practice of assessment—"assessment engineering," to use Luecht's (2002, 2007) term. We aim to bring to the surface the interplay among psychology (through the lens of KRs), technology, and assessment theory upon which this transformation is grounded.

The following section provides a brief review of important features of KRs. Five roles of KRs in assessment are then outlined. We note how KRs connect expertise with learning and assessment in a domain, and hence shape both instructional and assessment design. We then further develop and illustrate two of these roles, namely the design of assessment tasks around domain KRs and the creation of special KRs that help the assessment designer accomplish this. We place this discussion in the context of evidence-centered assessment design (ECD; Mislevy, Steinberg, & Almond, 2003; Mislevy & Haertel, 2006) to take advantage of KRs emerging from that work.

The ideas are illustrated with examples from three assessment projects. A relatively simple example based on Butterfield et al. (1985) concerning inductive reasoning tasks is interleaved through the discussion. Two more-complex examples are discussed in greater detail later in the paper. They concern a "generating examples" task type developed at Educational Testing Service (Bennett et al., 1999; Bennett, Morley, & Quardt, 2000; Katz, Lipps, & Trafton, 2002) and Cisco Systems' computer network simulation (CNS) assessments of design and troubleshooting (Behrens et al., 2004, Frezzo & Stanley, 2005, Williamson et al., 2004).

Knowledge Representations in Assessment

KRs play a central role in human cognition, as a means of identifying, expressing, communicating, and utilizing information in social spheres. Generally speaking, KRs are a vehicle for discourse, used either by a single individual (mediated cognition) or among individuals (distributed cognition), at one point in time or across multiple time points. They concern entities, relationships, and processes in some domain, and their organizational form is used to create, gather, store, transform, and use information more easily than would be accomplished without them. Markman's (1999, pp. 5–8) definition of a KR has four components:

- *A represented world*: The domain that the representations are about. The represented world might be the world outside the cognitive system or some other set of representations inside the system. That is, one set of representations can be about another set of representations.
- *A representing world*: The domain that contains the representations. (The terms "represented world" and "representing world" come from a classic paper by Palmer, 1978.)
- *Representing rules*: The representing world is related to the represented world through a set of rules that map elements of the represented world to elements of the representing world.
- *A process that uses the representation*: It makes no sense to talk about representations in the absence of processes. The combination of the first three components (a represented world, a representing world, and a set of representing rules) creates merely the potential for representation. Only when there is also a process that uses the representation does the system actually represent, and the capabilities of a system are defined only when there is both a representation and a process. Increasingly, as we will see in the case of assessment, these processes can be carried out digitally as well as perceptually, cognitively, or mechanically, as has been the case historically.

Some KRs, such as mathematical notation and computer languages, gain their power through symbol manipulation. After information has been encoded in the required form, operations can be carried out on the symbols to transform or combine the information in ways that would be difficult or impossible for a human to do unaided. A quotation from Whitehead (1911) is a propos:

> *By relieving the brain of all unnecessary work, a good notation sets it free to concentrate on more advanced problems, and, in effect, increases the mental power of the race. … Civilisation [sic] advances by extending the number of important operations which we can perform without thinking about them. (pp. 59,61)*

Other KRs, such as graphs and maps, encode information in ways that capitalize on humans' strengths in recognizing patterns and interpreting spatial relationships (see, for example, Lewandowsky & Behrens, 1999, on statistical graphs and maps):

> *The greatest possibilities of visual display lie in vividness and inescapability of the intended message. A visual display can stop your mental flow in its tracks, and make you think. A visual display can force you to notice what you never expected to see. One should see the intended at once; one should not even have to wait for it to appear (Tukey, 1990, p. 367).*

Many KRs use both symbolic and perceptual representation in varying mixtures (e.g., Tufte, 1990). A table exploits spatial arrangement to communicate the relevance of the organizing concepts of rows and columns for the subject of each cell (Mosenthal & Kirsch, 1989). Technology extends the power of KRs in several respects. Interactivity, as in working through a wizard to complete a tax form, and collaboration over a distance, as in online meeting workspaces that share computer applications, are two familiar examples. Digital KRs are particularly amenable to automated symbol manipulation, in ways and at speeds that far outstrip unaided human cognition. A central problem in human-computer interaction is developing and tuning the KRs through which people interact with computers to exploit these capabilities.

Properties of Knowledge Representations

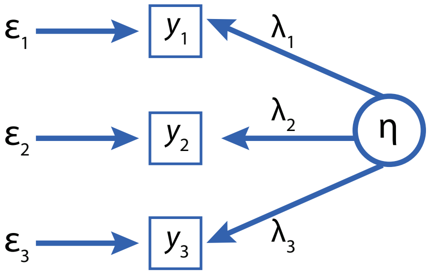
Several properties of KRs are relevant to their roles in assessment. One of the most important is that a KR does not attempt to include everything in the represented world, only certain entities and relationships. It highlights those entities and relationships, and facilitates thinking about them, talking about them, and working with them. This is the *ontology* of the KR. Unrepresented aspects of the represented world are considered irrelevant. The velocity of a falling body is represented by $v_0 + g\,t$, whether the body is a cannonball or a feather, whether it is falling in Austin or Tokyo. The breadth of applicability of KRs can be a strength. It is also a potential weakness in application when what is omitted from the mapping is important in the real-world situation, as when the velocity of a falling feather is lower because of air resistance. While carrying out reasoning within the representing world is important in learning to use KRs, it is just as important to learn when to apply them gainfully and how to recognize a potentially hazardous misfit (a central topic in statistics, for example; e.g., Belsley, Kuh, & Welch, 1980, on diagnostics in regression analysis).

In addition to focusing on only certain aspects of situations in the represented world, KRs are optimized for certain uses regarding those aspects. A domain of any complexity typically has many KRs, each tuned to different relationships and purposes. For example, matrix algebra, path diagrams, and computer code input are all used to represent factor analysis and structural equation models (SEMs) in psychometrics (Figure 1 shows two different representations of the same factor analysis model). The matrix equations admit to symbol-manipulation procedures for taking derivatives, which support algorithms for finding the values of the variables that fit the data best—finding maxima of multivariable likelihood functions is not something people do well in their heads. But graphical representations have advantages at the model-building stage, because the qualitative relationships among variables are immediately apparent and rapidly specified. Computer programs such as EQS (Bentler, 2006) allow the user to specify a model by working with a graphical interface, then generate code automatically to estimate the parameters with algorithms derived under the algebraic representation.

Note the essential role of technology in this process: The user working with a graphical interface is using an interactive computer-based representation that facilitates spatial thinking about relationships among variables; the computer representation is a digital encoding of the sequence of drags, drops, clicks, and typed characters; the computer program transforms this digital representation of user actions into another digital representation that would correspond in turn to an algebraic expression, upon which to carry out mathematical operations. The outcomes of these operations are re-expressed as human-friendly KRs such as graphs and tables of results, including human-accessible traces of processing such as changes in the log likelihood function at each cycle of an iterative process on computer-friendly KRs. We will see later in the CNS example how similar algorithmic conversions from one knowledge form to another provide advantages in computer-based assessment systems for domain analysis, task authoring, task presentation, interaction with the examinee, and automated scoring.

Figure 1: Matrix Algebra and Path Diagram Representations of a Factor Analysis Model

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix} \eta + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{pmatrix}$$



This attunement of KRs to different processes and purposes explains the presence of multiple KRs in a given domain (Ainsworth, 1999). Multiple KRs also occur when the complexities of real-world situations lend themselves to modeling at different levels or from different perspectives. In transmission genetics, for example, there are KRs for expressing relationships at the levels of species, individuals, cells, and molecules. Although each KR highlights entities and relationships at a certain level of analysis, relationships and constraints can cross levels and representational forms as well. The similarities of elements' chemical properties in a column of Mendeleev's periodic table correspond to similarities in electron shell diagrams. Translating information from one form to another is often a target of learning in content domains, as the process of solving a problem can take the form of a sequence of transformations within and between models, mediated by operations carried out with KRs.

One can speak of KRs at various levels of generality. For example, the elements and representational capabilities of Cartesian graphs and their attendant elements can be addressed at a general level, to display kinds of relationships that can be used to represent among variables in any domain. Certain knowledge associated with graphs can thus be learned and used (and assessed) across domains. Scatter plots in statistics and acceleration graphs in physics are both special cases of Cartesian graphs that can be studied in their own right, as patterns in graphs correspond to more specialized representations such as acceleration formulas, which are in turn grounded in the generative principles of that particular domain.

KRs have value because people can do things with them. Well-chosen KRs incorporate subtle and hard-won insights into a form that can be applied mechanically. Fifty years ago, an economist could win a Nobel prize for generating and solving from first principles the kinds of systems of linear equations that EQS users can apply today without knowing either calculus or matrix algebra. It is an advantage of a KR that a user can exploit deep principles without knowing them explicitly. To enjoy these benefits, however, the user must become attuned to the ways the KR offers to create, display, or transform information—its affordances, to use Gibson's (1966) term. The problem of designing KRs to best communicate information and affordances receives both practical and academic attention in fields such as graphics (e.g., Pinker, 1990) and human-computer interfaces (e.g., Card, Moran, & Newell, 1983). This research is prompted in part by the fact that KRs that can be expressed in symbolic form support multiple views and automated transformations. For example, CNS works back and forth between perceptual KRs for presenting and capturing information from examinees and symbolic KRs for evaluating their work and transforming information from one form to another.

How do KRs facilitate work? By focusing on recurrent patterns at a level above the particulars of any problem, KRs facilitate analogies across problems and domains. They make it easier to acquire and structure information. They coordinate work in projects that are so large or complex that no one can know all the details of all their facets. In such cases, KRs such as Gantt charts and object models help people understand their roles and connect their work with that of others. They provide a common language for people to express information and work with it in ways that tacitly incorporate experience from other times and other people. The form of a KR can indicate when information is missing. For example, representing text information in a matrix graphic organizer rather than text makes missing information more salient (Figure 2, next page). KRs such as blueprints, agendas, schedules, to-do lists are significant in planning, because they indicate what information is needed, how it is to be acted upon, and what a solution will look like. Collins and Fergusen (1993) emphasize that people can create new knowledge by using KRs by referring to them as "epistemic forms," and the ways that people use them as "epistemic games."

Figure 2: **What Information is Presented About Moths but Not About Butterflies? The Missing Element is Easier to See From the Matrix Organizer than in the Text**

Moths and Butterflies (text)

A moth has two sets of wings. It folds the wings down over its body when it rests. The moth has feathery antennae and spins a fuzzy cocoon. The moth goes through four stages of development.

A butterfly also goes through four stages of development and has two sets of wings. Its antennae, however, are long and thin with knobs at the ends. When a butterfly rests, its wings are straight up like outstretched hands.

Moths and Butterflies (matrix organizer)

	Moths	**Butterfiles**
Wings	Two sets	Two sets
Rest	Wings over body	Wings outstretched
Antennae	Feathery	Long, thin, with knobs
Cocoon	Fuzzy	—
Development	Four stages	Four stages

Roles of Knowledge Representations in Assessment

Looking at educational assessment through the lens of KRs reveals their presence throughout the enterprise, at different stages, at different levels, and with different purposes. The following sections discuss five key roles that KRs play in assessment:

1. An assessment is in itself a KR, which makes explicit the knowledge that is valued, ways it is used, and standards of good work.
2. The analysis of any domain in which learning is to be assessed must include the identification and analysis of the KRs in that domain (that is, the "domain KRs").
3. Assessment tasks can be structured around the knowledge, relationships, and uses of domain KRs.
4. "Design KRs" can be created to organize knowledge about a domain (including its domain KRs) in forms that support the design of instruction and assessment.

5. KRs from the disciplines of instructional design and assessment design can guide and structure the domain analyses noted in (2), the task construction noted in (3), and the creation and use of design KRs noted in (4).

Assessments Are Themselves Knowledge Representations

The analogy of assessment to measurement is vital to its conduct, but it is not sufficient. A student taking an assessment is engaged in a form of socially construed discourse (Gitomer & Steinberg, 1999), no less than a teenager playing a video game or a taxpayer completing an IRS 1040 form. This observation holds implications for assessment designers and students alike. Designers must always be aware that an assessment constitutes the most direct statement of the knowledge and skills that are valued, in effect if not in intention. The process of constructing an assessment, done thoughtfully, elicits an understanding of the knowledge that is targeted, the actions of students that provide evidence about it, and the circumstances under which that knowledge should be brought to bear (Wiggins, 1998). An assessment is a KR that communicates the targets of learning and the standards of performances to all stakeholders, and its construction serves educative purposes before the first examinee ever sees it.

In order to perform well in an assessment, students must not only have become facile with the targeted knowledge and skills, but they must also be able to work with them in the forms and under the conditions that characterize the assessment situation. That is, the students must be attuned to the affordances of the assessment as a form of KR. The more complex an assessment is, in terms of the embedded KRs students will interact with and the standards by which KRs that students produce will be evaluated, the more important it is to ensure that this attunement has taken place before the assessment begins. For students attempting to solve an interactive chemistry investigation with an unfamiliar computer interface, the interface can present more difficulties than the chemistry. Similarly, students cannot "explain" a solution to a mathematics problem until they understand the nature, the forms, and the expectations of exposition that are required to produce a "satisfactory explanation."

Identifying the Knowledge Representations of a Domain

Becoming an expert in a domain is a process of learning about the nature of knowledge in the domain, including terms, principles, patterns, and exemplars, and the nature of interaction among those who participate in that domain (Ericsson, 1996). The kinds of knowledge highlighted under both an acquisition metaphor and a participation metaphor (Sfrad, 1998) are required. KRs play central roles in both. KRs embody the important ideas and relationships in a domain, organize them so that they are the vehicle for doing work in the domain, define the language by which people acquire and communicate information in that domain, and coordinate the interactions of people as they work toward common ends. It is not much of an understatement to say that learning in a domain is learning to use the KRs of the domain—the domain KRs, as we call them here.

No analysis of a learning domain can be complete without an investigation of the KRs that are used in the domain and the situations in which they are used. Learning materials such as textbooks and exemplars are a natural place to begin, but the selection of KRs used in instruction can be biased toward "academic" KRs. Additional KRs used in practical work, perhaps informal or embedded in tools, are also part of the targeted domain, and learning how and when to use them is part of the targeted learning.

Structuring Tasks Around Domain Knowledge Representations

Assessment is reasoning about what students know, can do, or have accomplished more broadly, from evidence in the form of a relative handful of particular things they say, do, or make in particular situations. The situations in which the student is to act are defined in no small part through KRs. The various KRs that constitute an assessment task provide information about a situation to the student, suggest the nature of the problem, suggest the terms in which the problem is to be approached, offer clues as to the nature of a solution and the criteria of evaluation, and provide affordances for getting started. This is as true of open-ended performances or portfolios as it is of objective tests consisting of multiple-choice items. Furthermore, what the student says, does, or makes in response—the work products—are typically structured in terms of the KRs of the domain as well. Scalise and Gifford (2006) describe how, in technology-supported environments, having examinees complete or construct representations not only increases fidelity to the domain, but facilitates construct-driven automated scoring. Indeed, it is increasingly common, especially in simulation-based tasks like the CNS tasks, that complex interactive KRs constitute the environment in which the examinee thinks and acts.

Research on expertise reveals increasing expertise in the use of domain KRs as proficiency increases, in ways that hold implications for designing tasks and evaluating performances. As a first example, Kindfield's (1999) study of experts' and novices' use of diagrams to reason through genetics problems revealed an interesting reversal: Novices' drawings were often more complete and better proportioned than experts', but what distinguished experts' diagrams was that only the salient features tended to be shown, and the relationships important to the problem at hand were rendered with whatever accuracy was needed to solve the problem. That is, the experts' diagrams were more efficacious than those of the novices. As a second example, Cameron et al. (2000) found increasing proficiency in dental hygienists at increasing levels of experience with respect to their use of KRs such as radiographs, hard and soft tissue charts, and probing depth charts. Early stages of learning were marked by the ability to identify and interpret key features on a given single representation. Expert hygienists were distinguished from recently licensed hygienists by a superior ability to integrate information across multiple representations of different types, effectively constructing a model of a patient about whom all the representations were different, yet coherent, views of the same person.

A central idea for assessment design, and a central topic of the CNS example, is that a systematic analysis of the KRs in a domain—what they are, their features, and how people use them—is a foundation for principled generation of assessment tasks. An understanding of the entities and relationships of each KR and the relationships among them is developed in conjunction with an understanding of the kinds of reasoning or actions that one wants students to carry out using the KRs. The outcomes of this analysis lay the groundwork for schemas of tasks that focus on valued work in the domain in explicit ways, and exist at some level of generality above particular tasks. The level of generality of the KRs and the resulting schemas depends on the intended use, with the usual understanding that broad applicability of general forms trades off against the power of specific forms. These task construction schemas can themselves be expressed in terms of KRs. Hively, Patterson, and Page's (1968) item shells and Haladyna and Shindoll's (1989) item forms represented initial research along these lines, while more recent technology-based task construction frameworks include those of Bejar et al. (2003), Gierl, Zhou, and Alves (2008), and Mislevy et al. (2003).

At this point, we introduce an example from Butterfield et al. (1985) concerning theory-based generation of letter series tasks, a measure of inductive reasoning (Thurstone & Thurstone, 1941). Here are two examples based on the Primary Mental Abilities test battery (Thurstone & Thurstone, 1962):

Fill in the next letters in the series:

CDCDCD ___ ___ ___

ATBATAATBAT ___ ___ ___

This KR is an example of an *item type*—a particular kind of KR used in assessment to present information to an examinee and set expectations for a response. This particular KR consists of a series of symbols, read from left to right, arranged according to a pattern, or rule, that both explains the appearance of the symbols that are depicted and sets expectations for the symbols that would come next. The student's task is to determine the rule and make predictions. The blanks are affordances—the natural place to write the symbols that extend the pattern if you understand what the KR is about, but mysteries if you do not. Although these items require no specialized content knowledge other than the alphabet, they reflect the kind of reasoning required in more-complex inductive problems that do require more substantive knowledge, such as scientific inquiry. Because this is the representational form that the student works with, it is the domain KR in our first assessment example.

Representations for Designing Assessments in Given Domains

Advantages can be gained when the characteristics of the KRs can themselves be represented in higher-level KRs that are devised to serve the purposes of assessment design. We may call these "design KRs." Design KRs are related to domain KRs, but they are built for the purpose of generating domain KRs to be used in tasks. They describe salient features of task situations, in ways that both imply domain representations and indicate the kinds of reasoning and knowledge that the student will need to call upon. We shall see that the same representations can provide information to KRs used in other stages of assessment design and delivery, such as task selection and psychometric modeling (Bejar, 2002; Embretson, 1998).

Butterfield et al. (1985) created a design KR for the domain of letter series tasks described in the previous section. Letter series tasks had been used at least as early as Thurstone's research in 1941, in both practical applications and psychometric research. Task generation was idiosyncratic, however, and systematic examinations of both the structure of tasks and how people solve them were lacking (Butterfield). Simon and Kotovsky (1963) devised a symbol system to describe such tasks after they have been written, and their analysis is Butterfield's starting point for a KR that supports automated task generation in this domain. An abbreviated version and a few examples of the design KR for letter series rules convey the key ideas: Letter series tasks are composed of one or more strings of letters. Within a string, special relationships hold for moving from one letter to the next, such as identity (I), next letter (N), and back a letter (B). A rule is expressed by the relationships of letters within a string, and the strings' relationships to one another. The rule underlying the series CDCDCD is denoted by I1 I2, instantiated with C and D as the initial values of the first and second strings. The same rule instantiated with R and T as the initial values yields RTRTRT. The series MABMBCMCD is expressed as I1 I2 N2, with initial values M and A.

This design KR for expressing rules is obviously distinct from letter series tasks themselves, but they are related in ways that serve the purposes of the assessment designer. A rule expressed in the design KR grammar and initial string values suffices to produce a letter series task. Operations can be defined on rules expressed in the grammar of the KR to address issues of form, such as when two rules produce identical series. Other operations on rules address psychological issues such as memory load, as a function of calculable properties such as "Counts = # moving strings * (period – # adjacent identity relations)." Related operations can be used to address psychometric issues such as task difficulty (as in Embretson, 1998). The design KR for letter series tasks, therefore, has pragmatic connections to the task authoring, psychological argument, and measurement modeling layers of the assessment enterprise.

An early example of generative design KRs is Hively, Patterson, & Page's (1968) idea of "item forms" for generating whole number arithmetic items, two of which appear as Figure 3 (next page). Another example appears in Bormuth's (1970) work on generating "wh" questions from text. The KR is a syntactic representation of one or more propositions, which is amenable to symbolic transformations that yield questions that can be used to assess basic comprehension. Both of these examples provided KRs that enabled an assessment designer to map the structures and content of domain KRs (arithmetic items and English text) into more-abstract KRs that support transformations into tasks. The "generating examples" and CNS examples in later sections illustrate more recent work, in which the capability of computers to carry out symbol manipulation is exploited more fully in the automated construction of tasks through technology-based design KRs. At the time Bormuth (1970) introduced the "generating questions" approach mentioned above, for example, tasks were generated algorithmically but needed to be constructed by hand; few applications were carried out (Roid & Finn, 1977, describes one such application). With current natural-language processing capabilities, it would be a simple matter to construct "wh" questions from English text automatically.

Figure 3: Two "Item Forms" from Hively, Patterson, and Page (1968)

Descriptive Title	Sample Item	General Form	Generation Rules
Basic fact; Minuend > 10	13 –6	A –B	1. A=1a ; B=b 2. $(a<b)$ ε U 3. {H, V}
Borrow across zero	403 –138	A –B	1. # digits = {3,4} 2. $A=a_1a_2\ldots$; $B=b_1b_2\ldots$ 3. $(a_1>b_1)$, $(a_3<b_3)$, $(a_4\geq b_4)$, ε U_0 4. b_2 ε U_0 5. $a_2 = 0$ 6. P{{1,2,3},{4}}

Capital letters represent numerals, lower case represent digits.
x ε { — } means chose x with replacement from the set.
U = {1,2,…,9}; U_0={0,1,…,9}.

Knowledge Representations in the Discipline of Assessment Design

As long as assessment has been practiced, KRs have been developed to aid designers. Familiar examples include the aforementioned item types and item forms, test specifications (Davidson & Lynch, 2001, for a recent in-depth discussion), and content-by-process matrices often based on Bloom's (1956) taxonomy of educational objectives. These KRs are used to help designers generate items and assemble test forms. KRs used in the analysis of test data are also familiar, from the symbolic representations used in psychometric models to innovative displays used to summarize patterns in performance for students and their teachers. Schemas for rubrics to evaluate open-ended task performances are also widely used, allowing an assessor (such as a classroom teacher) to adapt a tested evaluation procedure to locally customized tasks; a number of tools are available in interactive formats on the Internet. Wiggins (1998) offers designers of performance assessment a number of templates and flowcharts, all with an eye toward connecting what is assessed with the goals of instruction.

Designing assessments of any complexity involves considerations at many levels: substantively grounded evidentiary arguments, design of operational elements such as tasks and scoring models, implementing the design in terms of specific tasks, and all the operational activities involved in actually carrying out the assessment. No single KR can encompass all this work; multiple, coordinated representations are required. Developing frameworks for assessment design, complete with a conceptual rationale and multiple supporting KRs, has been a focus of research in the assessment community in recent years (e.g., Almond, Steinberg & Mislevy, 2002; Embretson, 1998; Luecht, 2002, 2007, Wilson, 2005). The next section discusses one such approach in greater detail.

A Closer Look at KRs and Assessment Design

Evidence-centered assessment design (ECD) is a process of assessment design that involves gathering, organizing, and transforming information in a variety of representational forms, within the framework of a clearly articulated assessment argument. Under the ECD framework, KRs are integral at every step in the process of developing and using an assessment. This section starts with a brief overview of ECD and then, through this perspective, discusses and provides examples of KRs in assessment design.

A Brief Overview of Evidence-Centered Assessment Design

Central ideas in ECD are the assessment argument, layers of the assessment, and the role of KRs in designing and implementing assessments. Messick (1994, p. 16) concisely lays out the key aspects of an assessment argument by asking "what complex of knowledge, skills, or other attributes should be assessed? Next, what behaviors or performances should reveal those constructs, and what tasks or situations should elicit those behaviors?" All of the many terms, concepts, representations, and structures in ECD are aimed at constructing a coherent assessment argument and building machinery to implement it.

Adapting a "layers" metaphor from architecture and software engineering, ECD organizes the design process in terms of the following layers: domain analysis, domain modeling, conceptual assessment framework, assessment implementation, and assessment delivery (Mislevy & Riconscente, 2006). The fundamental work in assessment design can be viewed as creating, transforming, and using information in the form of KRs within and between these layers. Table 1 (next page) summarizes these layers in terms of their roles, key entities (for example, concepts and building-blocks), and the KRs that assist in achieving each layer's purpose. The layering suggests a sequential design process, but cycles of iteration and refinement across layers are the norm.

Table 1: Layers of Evidence-Centered Design

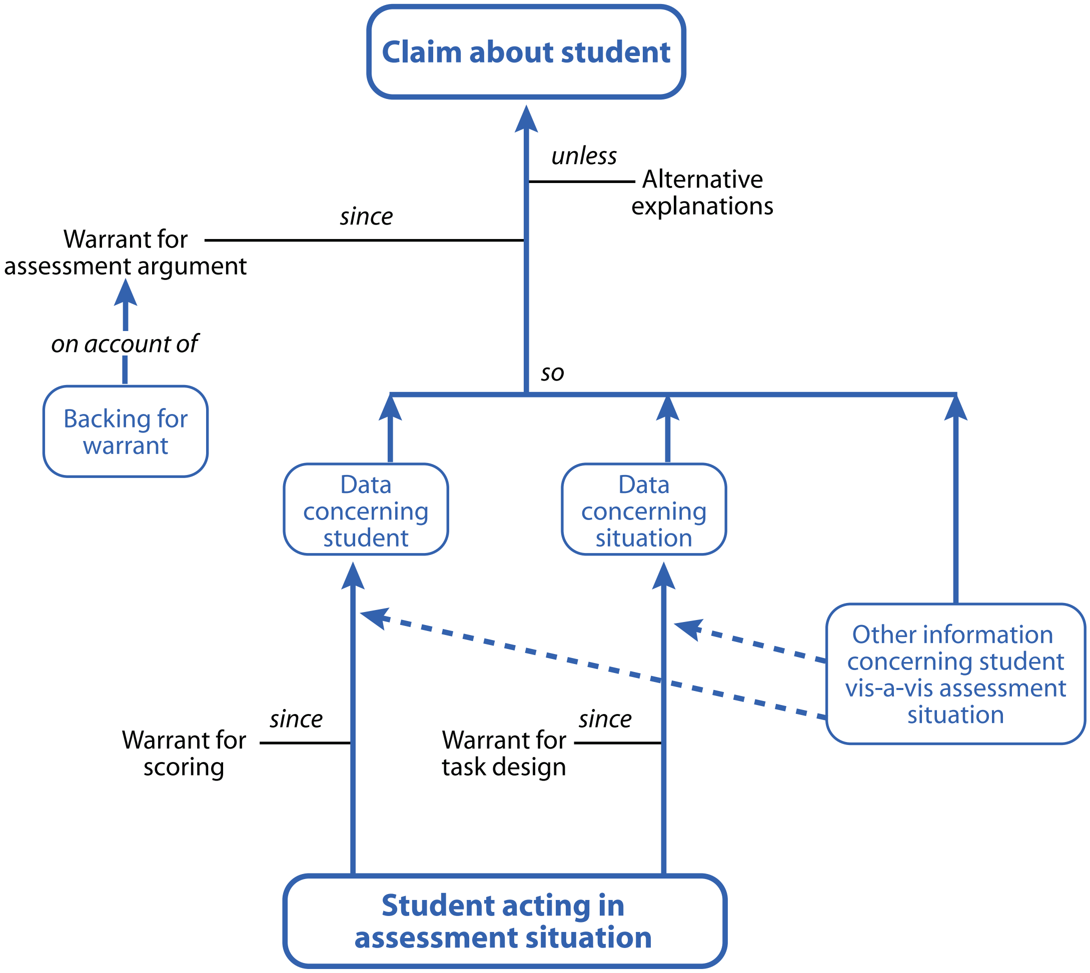
Layer	Role	Key Entities	Examples of Knowledge Representations
Domain Analysis	Gather substantive information about the domain of interest that has direct implications for assessment: how knowledge is constructed, acquired, used, and communicated.	Domain concepts, terminology, tools, knowledge representations, analyses, situations of use, patterns of interaction.	Content standards, concept maps (e.g., Atlas of Science Literacy, AAAS, 2001). Representational forms and symbol systems of domain of interest, e.g., maps, algebraic notation, computer interfaces.
Domain Modeling	Express assessment argument in narrative form based on information from domain analysis.	Knowledge, skills, and abilities; characteristic and variable task features; potential work products and observations.	Assessment argument diagrams, design patterns, content-by-process matrices.
Conceptual Assessment Framework	Express assessment argument in structures and specifications for tasks and tests, evaluation procedures, measurement models.	Student, evidence, and task models; student model, observable, and task model variables; rubrics; measurement models; test assembly specifications.	Test specifications; algebraic & graphical KRs of measurement models; task template; item generation models; generic rubrics; automated scoring code.
Assessment	Implement assessment, including presentation-ready tasks, scoring guides or automated evaluation procedures, and calibrated measurement models.	Task materials (including all materials, tools, affordances); pilot test data for honing evaluation procedures and fitting measurement models.	Coded algorithms to render tasks, interact with examinees, evaluate work products; tasks as displayed; IMS/QTI representation of materials; ASCII files of parameters.
Assessment Delivery	Coordinate interactions of students and tasks: task-and test-level scoring; reporting.	Tasks as presented; work products as created; scores as evaluated.	Renderings of materials; numerical and graphical score summaries; IMS/QTI results files.

The first layer in the process of designing an assessment, *domain analysis*, lays the foundation for later layers by defining the knowledge, skills, and abilities (KSAs) that assessment users want to make inferences about, the student behaviors they can base their inferences on, and the situations that will elicit those behaviors. A critical part of domain analysis includes identification of KRs important to the domain, because expertise in a domain necessarily includes knowledge of and understanding of how and when to use the KRs in that domain.

At the next layer, *domain modeling*, KRs within the domain of assessment design come into play in the form of assessment argument diagrams (Bachman, 2003, Mislevy, 2003, 2006; see Figure 4 for the basic structure, adapted from Toulmin, 1958), content-by-process matrices, and the design patterns that will be discussed in more depth in the next section.

Using these KRs, domain modeling structures the outcomes of domain analysis in a form that reflects the structure of an assessment argument, in order to ground the more technical student, evidence, and task models that are required in the subsequent Conceptual Assessment Framework (CAF) layer.

Figure 4: An Assessment Argument Diagram



The *conceptual assessment framework (CAF)* concerns the technical specifications for the materials and processes that embody assessments. The central models in the CAF are the student model, the evidence model, and the task model (Figure 5, page 22). In addition, the assembly model governs how tasks are assembled into tests, a presentation model indicates the requirements for interaction with a student (for example, simulator requirements), and the delivery model specifies requirements for the operational setting. An assessment argument laid out in narrative form at the domain-modeling layer is here expressed in terms of specifications for tasks, measurement models, scoring methods, and delivery requirements. Details about task features, measurement-model parameters, stimulus material specifications, and the like are expressed in terms of KRs and data structures that we will say more about later in this section, which guide their implementation and ensure their coordination.

With information from the models in the CAF, delivery of an assessment from an ECD perspective is defined by a four-process architecture (Figure 6, next page). Starting in the upper left corner of Figure 6, the *activity selection process* selects a task (tasks include items, sets of items, or other activities) and directs the *presentation process* for display to the examinee. When the examinee has finished interacting with the item, the results (a *work product*) are sent to *response processing*. Information from the *task model* defined in the CAF provides the basis for the *presentation process* and *work product* specifications. From information outlined in the *evaluation model* of the CAF, the *response process* identifies essential *observations* about the results and passes them to the *summary scoring process*, which updates the *scoring record* about the examinee. The *scoring record* describes knowledge about the student-model variables articulated in the *student model* of the CAF. All four processes add information to the *results database*. The *activity selection* process again makes a decision about what to do next, based on the current scoring record of the participant or other criteria.

The preceding brief outline is not sufficient to explain the roles and interplay of the processes, or the way that this structure supports the design of technology-based assessment tasks and delivery systems; the reader is referred to Almond, Sternberg, & Mislevy (2002). What is important for this presentation is that every message that passes from one process to another is expressed in terms of some KR. It has been produced by the sender, be it a human or computer, and provided in a form that the receiver, again a human or a computer, can use to carry out some other function essential to the operation of the assessment. The following sections provide examples.

Figure 5: The Central Models of the Conceptual Assessment Framework (CAF)

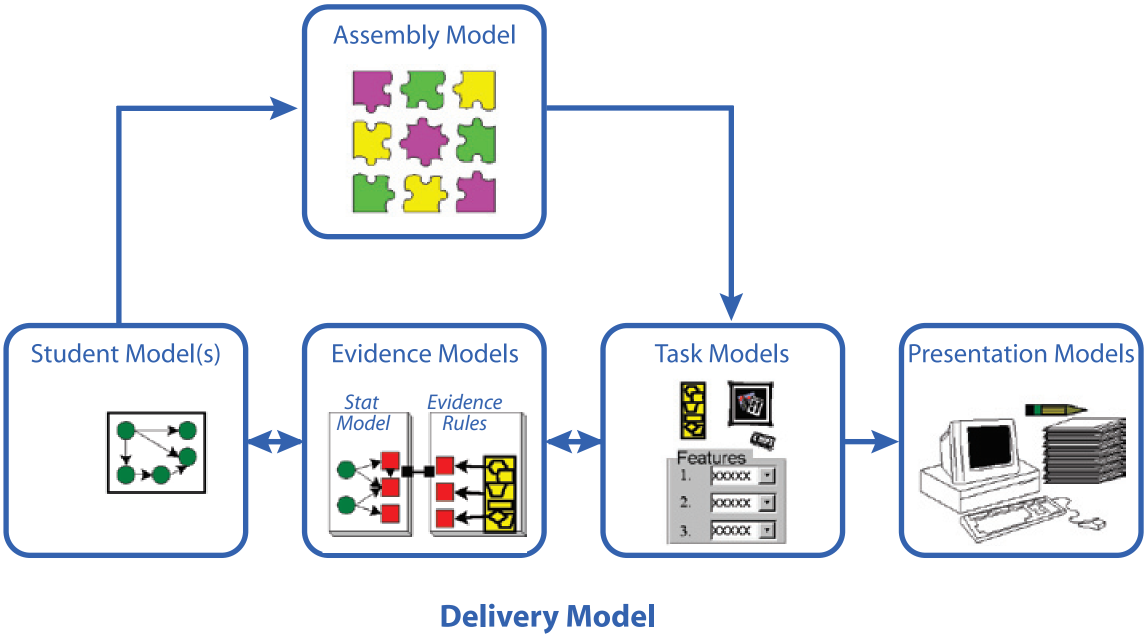
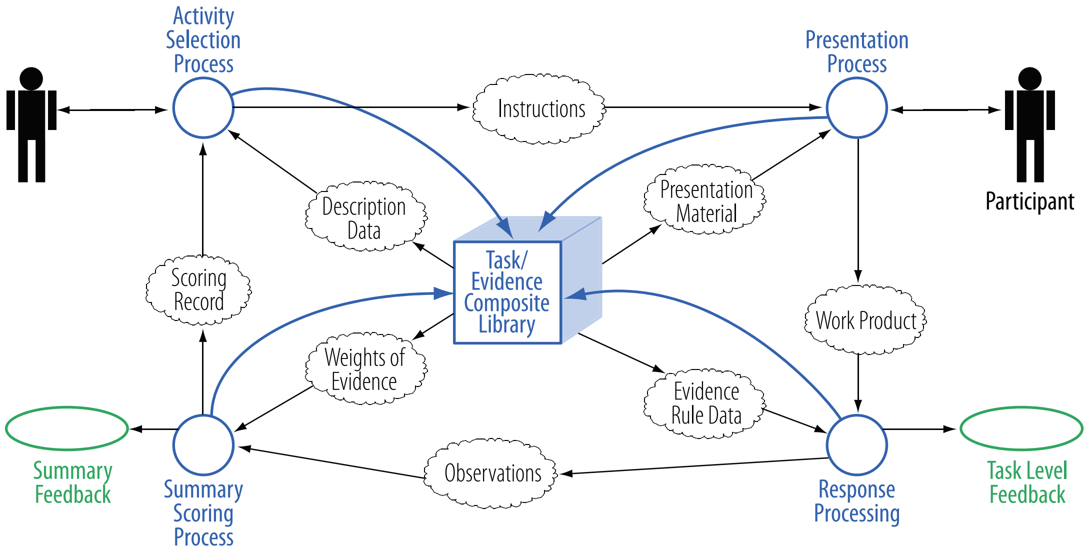


Figure 6: The Four Principle Processes in the Assessment Cycle



Domain Reasoning, Knowledge Representations, and Task Design

The ECD process affirms the idea that analysis of the KRs central to a given domain is integral to generating assessment tasks in that domain. Essential to this idea is the connection between a given domain KR itself, reasoning in the domain, and the way people use it in practice. This is critical because the knowledge needed to use a domain KR in a particular circumstance is often what we want to draw inferences about. Identifying and articulating the relationship between using specific KRs in particular situations and the type of knowledge elicited is an important link in the assessment design process. Identification of these relationships during the domain analysis process sets up the construction of arguments in domain modeling, which in turn sets up the creation of schemas for designing tasks.

Butterfield et al.'s (1985) letter series example provides an example of the interplay between KRs and knowledge. In this example, the KR, a pattern of letters, provides a way for both task designers and examinees to reason about the underlying pattern. In essence, this KR allows for assessment of the inductive reasoning ability of the test-taker; the KR structure itself becomes a tool for assessing this knowledge.

Checklists and behavioral inventories are examples of KRs that have long been used to ground licensure and certification tests. As epistemic forms, they provide structure to the job analyst's task of identifying the nature and frequency of tasks professionals carry out, from which assessment tasks will be devised.

More recent work in cognitive task analysis addresses the nature, organization, and use of knowledge that tasks employ (Schraagen, Chipman & Shalin, 2000). This allows for distinctions between different types of knowledge and skills that one may want to evoke from an examinee, including declarative, procedural, or strategic knowledge, which may all be associated with one particular domain KR. The information is collected during the domain analysis phase of the assessment design. For example, Shute, Torreano, and Willis's (2000) automated knowledge elicitation tool DNA (Decompose, Network, Assess) provides structured, user-friendly web forms to elicit domain experts' input on declarative, procedural, and conceptual-knowledge requirements of common tasks in the domain. The DNA tool is an interactive design KR, capitalizing on technology and the wizard metaphor to elicit and structure domain information from subject-matter experts, and to store it in digital forms that can be transformed to support domain modeling, the next step in the design process.

In addition to the argument schema shown in Figure 4 (page 20), another KR that has been developed for work in the domain modeling layer is the *design pattern* (Mislevy et al., 2003). Design patterns encapsulate knowledge about ways to address assessment challenges that recur across domains or within particular domains, organized in categories that connect to elements of an assessment argument on the one hand, and point ahead toward the more technical elements of the CAF. For example, Table 2 shows selected portions of a design pattern for *problem-solving in finite systems*, a valued skill in both everyday life (why won't this door close?) and in technical domains such as aircraft repair, computer programming, and the troubleshooting of computer networks addressed by the CNS tasks. A design pattern for this particular skill can be utilized across domains because it capitalizes on similar patterns of problem-solving reasoning in each. Within any given domain, multiple design patterns can be used to target the knowledge, skills and abilities of interest—such as building a teamwork task around troubleshooting, working-in-groups, and self-monitoring design patterns.

Table 2: Portions of a Design Pattern for Problem-Solving in Finite Systems

Summary	Students are presented a problem of determining the state of a system, and methods for gathering information about its state. No available diagnostic procedure is definitive; each rules in some possibilities and rules out others.
Rationale	Integrated knowledge structures, characteristic of effective problem solvers, are displayed in the ability to represent a problem, select and execute goal-directed strategies, monitor and adjust performance, and offer complete, coherent explanations. In particular, problem-solving to determine the state of a finite system with a set of tests requires an understanding of the procedures that can be applied to rule sets of states in or out, being able to interpret the results of the tests, synthesizing their information to determine what states are still possible after a series of tests, and being able to choose a next test that will effectively narrow the search space.
Focal knowledge, skills, and abilities	• Ability to apply knowledge of system and component functioning to solve a problem. • Ability to generate and elaborate explanations of task-relevant concepts. • Ability to build a mental model or representation of a problem to guide solution. • Ability to devise and manage problem-solving procedure.
Additional knowledge, skills, and abilities	• Domain knowledge. • Capability to carry out tests. • Ability to coordinated problem-solving with others (if required).
Characteristic task features	• Statement of problem provides system, initial conditions, and set of test procedures. • System with imperfectly known state (e.g., fault, unknown components). • There is a finite (though possibly large) space of possibilities of the system state. • Each test procedure rules some aspects of system state in and others out.

(continued on the next page)

Table 2: Portions of a Design Pattern for Problem-Solving in Finite Systems (continued)

Variable task features	• Level and nature of content knowledge required to solve problem. • Degree of domain familiarity required. • What is the fault(s)? • Fault simple, compound, intermittent? • Complexity of system to troubleshoot. • Degree of scaffolding or prompting. • Individual work, work with a partner, or as a member of a group? • Number of diagnostic procedures to choose from. • Redundant diagnostic procedures? • Overlapping diagnostic procedures?
Potential observable variables	• Correctness of solution. • Quality of evidence to support conclusions. • Quality of explanation of task-specific concepts. • Adequacy of problem representation or problem-solving plan. • Appropriateness of solution strategies. • Frequency and flexibility of self-monitoring. • Efficiency of solution. • Accuracy of deductions at each step.
Potential work products	• Written or verbal description/identification of where the problem is or what the solution is to the problem. • Illustration of problem solution and/or written justification for "Here is how I know." • Verbal or written description of anticipated problem-solving approach. • Verbal or written explanation of task-specific concepts. • Log or observation of student actions. • Observation data/log-file/think-aloud protocols during solution. • Indication of possibilities are ruled in or out by a given test procedure. • Indication of which possibilities are ruled in or out by all test procedures given thus far, at any point during the solution.

The design pattern structure can be used to address the type of proficiencies that people employ when using domain KRs. For example, in model-based reasoning an initial model, usually expressed in the form of a KR, is created and iteratively revised as it is tested in real-world situations (Stewart & Hafner, 1994). The Architectural Registry Examination (ARE) (Bejar & Braun, 1999) utilizes this type of reasoning with a computer-aided design (CAD) system that has examinees produce a domain KR in the form of a site plan. At each step in this iterative process, examinees react to and modify their design based on their previous designs and remaining constraints for the design (Katz, 1994). The steps examinees take in this process (all, it may be noted, within the technology-based simulation environment that is itself an interactive KR) become a critical aspect of assessing their level of expertise in architectural design.

Thus, the design pattern KR serves first as an epistemic form to synthesize experience and analysis of classes of valued work in ways that will support assessment design. It is then a source of information for the task author creating such specific tasks or task models for a specific context. It provides grounding for the validity of tasks created in this manner by making explicit the link between the features, requirements, and evaluation procedures of a task and the knowledge and skills that are valued in the domain (Bennett & Bejar, 1998).

While the sample design pattern illustrated in Table 2 is a static form, affordances provided by technology have been employed to facilitate their construction by geographically dispersed design teams and their interactive use by task authors. That is, the usefulness and efficiency of design patterns as a KR has been leveraged by embedding them in digital form, and taking advantage of technological affordances to help people build them and use them. The form in which design patterns are created is an object model that can be built by a dispersed team in real time over the Internet using a collaborative virtual work space (Hamel & Shank, 2005). A "writer-friendly" online version of the design pattern structure presents item writers with a concise summary version of the pattern but allows them to follow links for additional discussion and examples of the various attribute entries, and to highlight entries from different attribute categories that are related to one another with regard to task design choices (Mislevy & Liu, 2009).

Knowledge Representations for Creating, Presenting, and Scoring Tasks

After the evidentiary argument has been defined at the domain analysis and domain modeling layers, the next layers focus attention on structuring and generating actual tasks. These are the CAF layer, in which student, evidence, and task models are articulated, and the Implementation layer, which includes task generation. This section notes roles that KRs play in these processes.

Task Creation

In domain analysis, the designer identifies situations in which practitioners in a domain use the KSAs of interest, and on this basis in domain modeling the designer frames, in the KR of design patterns, paradigmatic situations to elicit those KSAs (recall Table 1). In the CAF, more detailed *task models* are created. A task model is a design KR that structures the authoring of the actual tasks that will be presented to the student. It describes the environment in which students will act to provide the data necessary to make inferences about KSAs, including the domain KRs that will be used to provide information to the examinees and to serve as work spaces and tools for them, and in which they will express the products and processes of their work. The values of the *task model variables* identified in a task model provide specifications such as the form of the work product, the materials necessary, and other features of the setting, all of which are grounded in the original assessment argument and play a variety of roles in task construction, presentation, scoring, and interpretation of results (Mislevy et al., 2002).

Figure 7 (next page) shows a schematic diagram of the relationship between the task model variables (on the right-hand side) and the assessment implementation and delivery process. The task model variables, which in this example include the language in which the task will be presented, inform the task design as well as the evidence portion of the process. As described in Mislevy et al. (2002), these attributes in the task model KR provide information for KRs used in task authoring, task selection, automated scoring, psychometric modeling, and score reporting.

A task model, then, is a design KR that includes details about how the information the tasks elicit is related to other components of the assessment. The task model also explicates what particular features are necessary to include and which are variable, or optional. This general idea has been embodied in a variety of particular forms. For illustration we use here the *task template* (Riconscente, Mislevy, & Hamel, 2005) developed in the Principled Assessment Design for Inquiry (PADI) project to describe task models more specifically. Task authors can use the template as a blueprint to create actual tasks that are grounded in the original assessment argument, without needing to reconstruct this reasoning. As an example, Figure 8 (page 29) shows an example of a PADI task template for BioKIDS, a project that helps students learn science inquiry (Gotwals & Songer, 2006). As can be seen in this example, the template lays out the student and measurement models in conjunction with the task model. Further, the template articulates particular materials, activities, and tools associated with the task template. In this way, the task template is connected to the chain of reasoning that occurs at the domain analysis and domain modeling layers.

Figure 7: Schematic Showing the Roles of Task Model Variables

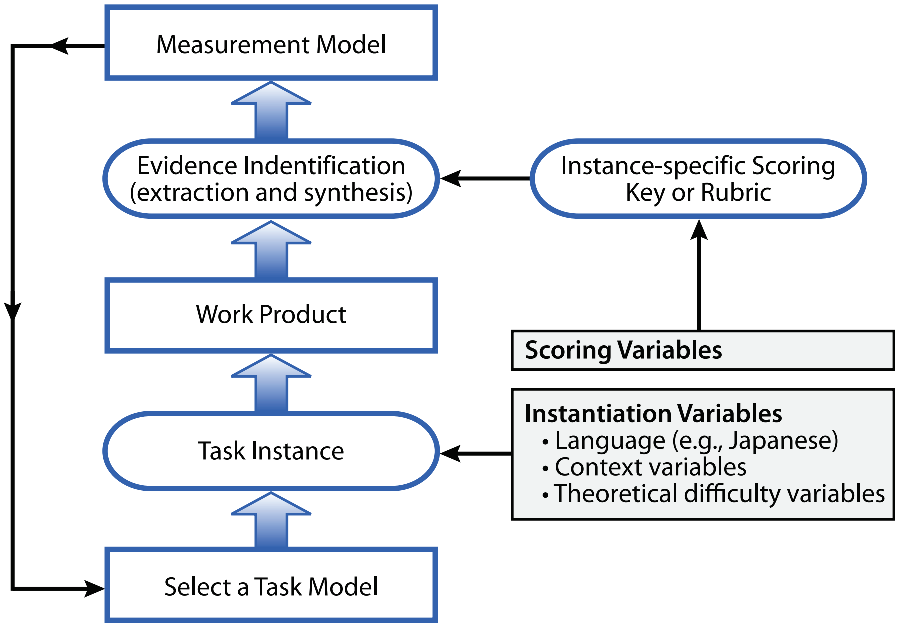
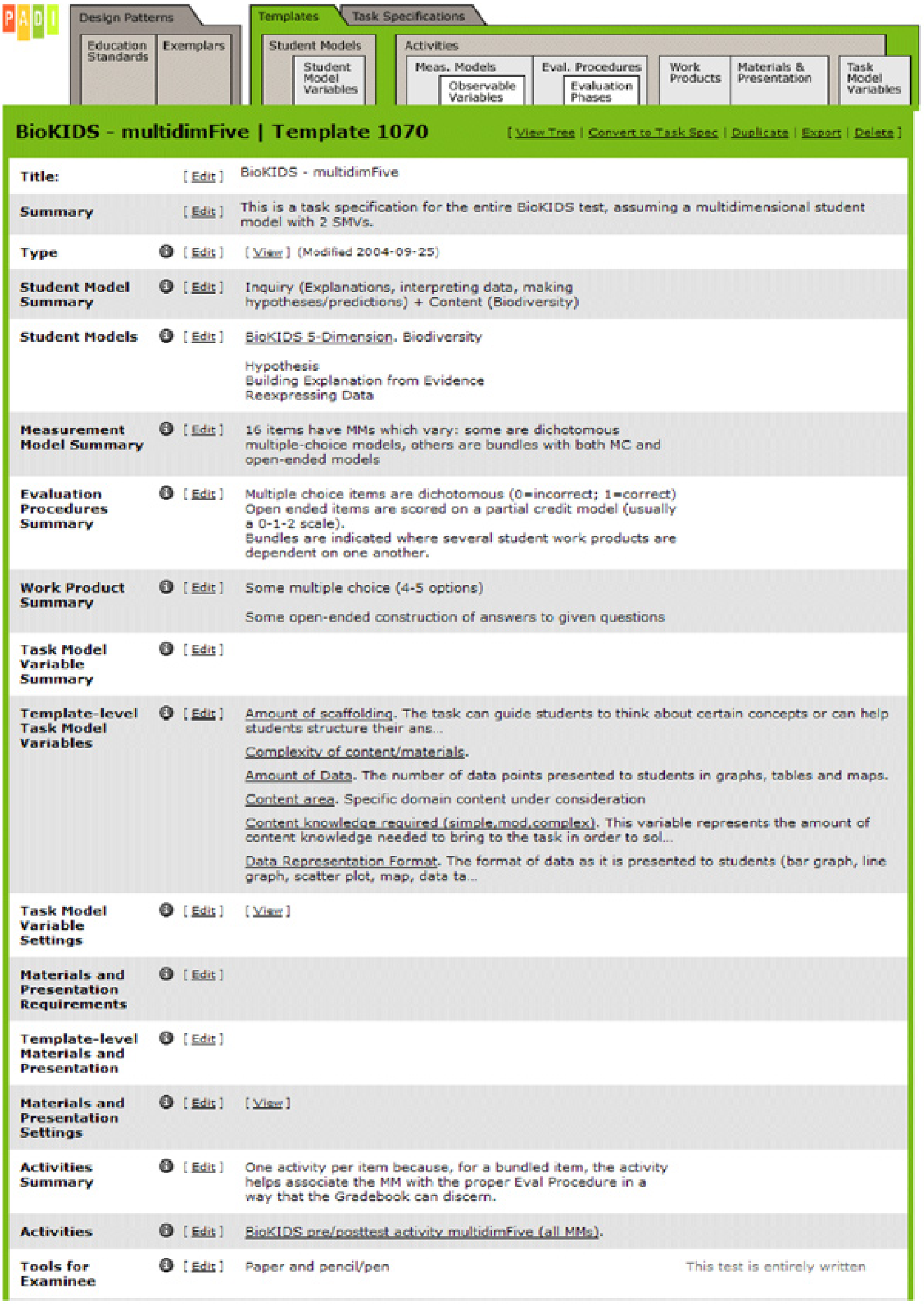

Measurement Model
Evidence Indentification (extraction and synthesis)
Instance-specific Scoring Key or Rubric
Work Product
Scoring Variables
Task Instance
Instantiation Variables
• Language (e.g., Japanese)
• Context variables
• Theoretical difficulty variables
Select a Task Model

Figure 8: A BioKIDS Template in PADI Design System



BioKIDS - multidimFive | Template 1070

Title:	[Edit]	BioKIDS - multidimFive
Summary	[Edit]	This is a task specification for the entire BioKIDS test, assuming a multidimensional student model with 2 SMVs.
Type	ⓘ [Edit]	[View] (Modified 2004-09-25)
Student Model Summary	ⓘ [Edit]	Inquiry (Explanations, interpreting data, making hypotheses/predictions) + Content (Biodiversity)
Student Models	ⓘ [Edit]	BioKIDS 5-Dimension. Biodiversity Hypothesis Building Explanation from Evidence Reexpressing Data
Measurement Model Summary	ⓘ [Edit]	16 items have MMs which vary: some are dichotomous multiple-choice models, others are bundles with both MC and open-ended models
Evaluation Procedures Summary	ⓘ [Edit]	Multiple choice items are dichotomous (0=incorrect; 1=correct) Open ended items are scored on a partial credit model (usually a 0-1-2 scale). Bundles are indicated where several student work products are dependent on one another.
Work Product Summary	ⓘ [Edit]	Some multiple choice (4-5 options) Some open-ended construction of answers to given questions
Task Model Variable Summary	ⓘ [Edit]	
Template-level Task Model Variables	ⓘ [Edit]	Amount of scaffolding. The task can guide students to think about certain concepts or can help students structure their ans... Complexity of content/materials. Amount of Data. The number of data points presented to students in graphs, tables and maps. Content area. Specific domain content under consideration Content knowledge required (simple,mod,complex). This variable represents the amount of content knowledge needed to bring to the task in order to sol... Data Representation Format. The format of data as it is presented to students (bar graph, line graph, scatter plot, map, data ta...
Task Model Variable Settings	ⓘ [Edit]	[View]
Materials and Presentation Requirements	ⓘ [Edit]	
Template-level Materials and Presentation	ⓘ [Edit]	
Materials and Presentation Settings	ⓘ [Edit]	[View]
Activities Summary	ⓘ [Edit]	One activity per item because, for a bundled item, the activity helps associate the MM with the proper Eval Procedure in a way that the Gradebook can discern.
Activities	ⓘ [Edit]	BioKIDS pre/posttest activity multidimFive (all MMs).
Tools for Examinee	ⓘ [Edit]	Paper and pencil/pen This test is entirely written

Another advantage of task models as design KRs, beyond ensured instantiation of the assessment argument at the task level, is their potential for guiding the reusability and adaptability of tasks to different forms or assessments. Hively et al.'s "item forms" provide an early example of this type of design KR. Item forms and item models provide item-level templates that can be adapted to a number of different assessments through changes in task features. Such templates allow the assessment designer the flexibility of adapting particular item types or tasks without losing the connection to the original assessment argument. This provides both efficiency and validity in task creation. Continuing with the example from the Butterfield et al. (1985) letter-series task, one can imagine using an "item form" approach whereby particular features of the letter-series task change (for example, letters, pattern) to create distinct items assessing the same reasoning.

When a task model is in digital form and the slots are appropriately filled, the resulting form can serve as input to subsequent processes to create tasks in the forms in which they are needed in implementation and presentation (as in Bejar et al., 2003, Gierl et al., 2008, Hamel, Mislevy, & Winters, 2008, and Hamel & Schank, 2006). Two examples of programs that can facilitate task authoring using the idea of item templates are Mathematics Test Creation Assistant (TCA, Singley & Bennett, 2002) and the Free-Response Authoring, Delivery, and Scoring System (FRADSS, Katz, 1995). Both of these tools allow for creation of multiple items from particular item models or item objects that are at a more general level of abstraction. Like PADI task templates, item forms and models support efficiency in their potential for reusability, as well as validity in their connection to the assessment argument laid out in the domain analysis phase.

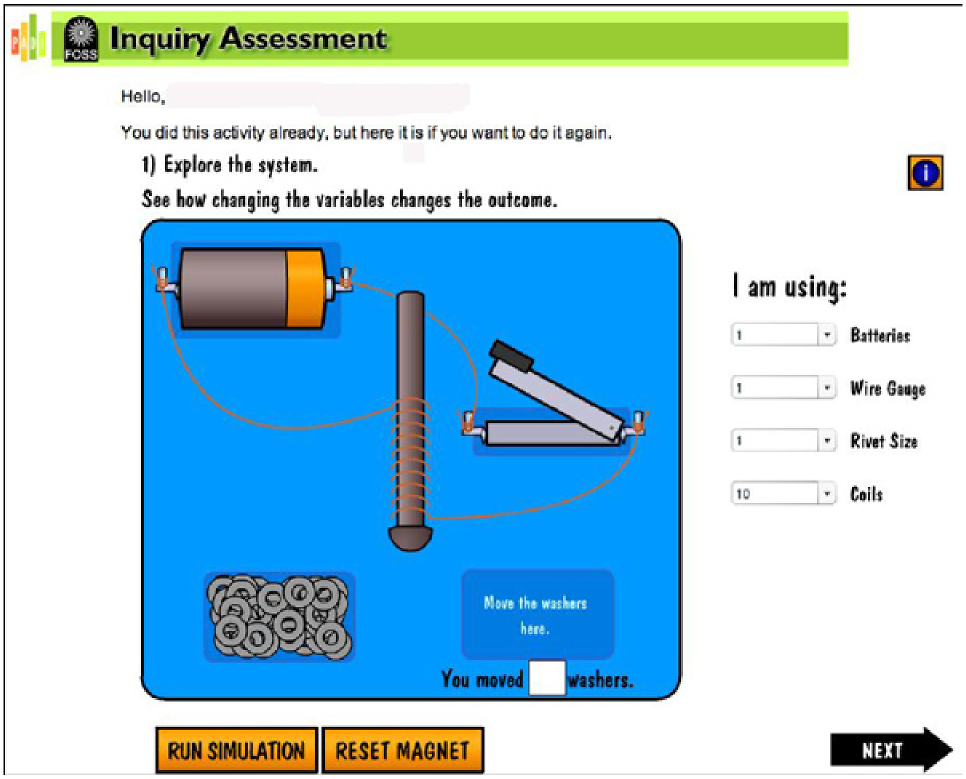
KRs play an important role in the decisions that are made about the environment around the task. For example, choice of the format (for example, paper and pencil or computer-based; multiple-choice or diagram with essay) and the materials (for example, physical manipulatives) will all be shaped by the KRs that are critical to the domain, as identified in the domain analysis phase and carried through to the task template. This aspect of task authoring is discussed in further depth in the next section on task presentation.

Task Presentation

KRs are important for task presentation in several ways. First, the tasks themselves can be considered KRs. They are designed, based on the assessment argument, to be KRs that examinees must respond or react to in some manner, producing a work product that will be subsequently evaluated. Most often, a task employs important domain KRs to achieve this. Mathematics tasks use diagrams and mathematical notation, social studies tasks use maps and graphs, and music tests use musical notation. The CNS utilizes symbols of network systems to assess examinees' understanding of network troubleshooting. Thus, the presentation of the tasks in this environment necessarily includes KR symbols, formats, and manipulations that the test-taker must be able to understand and use.

An example of a task as the examinee experiences it (in contrast to the task object KR, in the IMS/QTI xml form that the presentation process uses to render this view) is depicted in Figure 9. This screen shot is of a task from the Full Option Science System (FOSS) project, in which science phenomena are simulated in a computer environment. For this particular example, examinees are asked to interact with the symbols on the screen to simulate electrical circuits. A number of domain KRs are present in this example, such as the battery and switch. As a technology-based KR itself, the simulation environment affords interaction to the examinees so that the real-world implications of their actions with the simulated components can be visualized. In this way, the KRs have been tuned both to cognition in the domain and to the elements of an assessment argument.

Figure 9: Prompt from FOSS/ASK Simulation



Inquiry Assessment

Hello,

You did this activity already, but here it is if you want to do it again.

1) Explore the system.

See how changing the variables changes the outcome.

I am using:

1	Batteries
1	Wire Gauge
1	Rivet Size
10	Coils

Move the washers here.

You moved □ washers.

Decisions regarding what stimulus materials, resources, and levels of scaffolding will be provided to examinees are all described in the task model. These decisions are often affected by the type of work product that is derived for a particular task. With the FOSS example, the work products produced for this item are similar in form to many others from the tasks created with the same template.

Just as specifications for particular tasks are articulated in the task model, the presentation model provides specifications for rendering the task in a particular environment. For example, a presentation model for a computer-based assessment will be different from one for a paper-based test, even though the two might have identical task and evidence models. This flexibility is yet another example of the way in which the ECD approach enables adaptability and reusability of tasks.

Finally, design KRs also play a role in facilitating presentation of tasks across the various aspects of assessment delivery. For example, the IMS Question and Test Interoperability (QTI) specification is an assessment KR that allows for interchange of information between authoring tools, item banks, test construction systems, and assessment delivery systems. In this way, the QTI aids in creating and presenting tasks more efficiently, by providing a shared language for KRs that are used and produced in computer-based assessment (Almond, Steinberg, & Mislevy, 2002).

Task Scoring

Articulating the student model requires specifying the student-model variables. Each student-model variable corresponds to some aspect of knowledge, skill, ability, or proficiency, presumed to drive probabilities of observable responses. They will be the variables in a latent variable model such as an IRT, latent class, cognitive diagnosis, or Bayes net model. Psychometric models such as these use probability-based methods to ground inferences about students. From the perspective of ECD, the student model and the *measurement submodel* of the evidence model are KRs that support probability-based reasoning about examinees based on evaluations of their performances. Structured around recurring evidentiary themes, measurement model fragments can be fit together flexibly for different problems and different kinds of data (Conati, Gertner, & VanLehn, 2002; Mislevy, 2006; Rupp, 2002). Being able to automatically assemble probability models in light of purposes and evolving conditions, as in simulation-based assessment, is an example of what engineers call "knowledge-based model construction" (Breese, Goldman, & Wellman, 1994). Its implementation depends on developing KRs that encode key features of situations to guide the assembly of the measurement model and student model KRs.

The *evaluative submodel* of the evidence model involves identifying and evaluating features of the examinee work product, in terms of values for the observable variables that are used by the measurement submodel to update the values of student model variables. We have discussed how what examinees say, do, or make to provide evidence in assessments is often expressed in terms of domain KRs, which examinees create, complete, transform, or interrelate—this leveraging of domain KRs being central to proficiency in the domain of interest. Students produce these response KRs in their interactions with the presentation process. They constitute the message passed to the evidence evaluation process.

What is important here from the perspective of representation is that the form of the work product, as a KR, can be tuned to identifying and evaluating the features that convey evidence about the examinee's proficiencies. The work product KR must capture traces of the cognitive processes that produced it, no matter whether the evaluation is carried out by humans or automatically (Messick, 1994). Taking advantage of developments in technology to evaluate performances requires attention not just to the form of the work product KR and the procedures to be carried out, but also to virtually every link in the chain of reasoning that comprises the assessment argument (Bennett & Bejar, 1998). To this end, the Williamson et al. (2006)-edited volume *Automated Scoring of Complex Tasks in Computer-Based Testing* contains chapters describing various methodologies for automated scoring of KRs from performance assessments from the perspective of ECD. In a later section, we discuss automated scoring procedures used in CNS tasks, which adapt ideas from both the rule-based algorithms for scoring the log of patient management problems in the National Board of Medical Examiners' *Primum* assessment (Margolis & Clauser, 2006) and the natural language processing techniques used in automated scoring of essays (Deane, 2006).

The KR of multiple-choice response format revolutionized testing first when it was introduced in the early decades of the twentieth century, because it virtually eliminated judgment in evaluation, and then again in the middle of the twentieth century when machine-based scoring of multiple-choice items made standardized testing economical at vastly larger scales. Current work focuses on the use of more ecologically valid KRs as work products; that is, examinees' performance in directly constructing, completing, or transforming domain KRs. To accomplish this objective economically requires KRs that in one view the examinee can interact with, but that in another view support both customizable automated evaluation procedures and flexible reuse across assessment domains and purposes. The key to successful automated scoring is the articulation of the cognitive psychology underlying the use of the domain KRs, which determines how assessment design and implementation KRs are structured and processed to provide the necessary evidence in the assessment argument.

"Generating Examples" Tasks

This section looks more closely at an innovative task family for use in large-scale testing, through the lens of KRs. Bennett, Steffen, Singley, Morley, and Jacquemin (1997) developed the mathematical expression (ME) response type that allows presentation of any item for which the answer is a rational symbolic expression. It was created primarily to present mathematical modeling problems such as the following:

> A normal line to a curve at a point is a line perpendicular to the tangent line at the point. The equation of the normal line to the curve $y = 2x^2$ at the point (1,2) is given by ________.

Such questions typically describe a situation in one representational form (verbal), which the examinee must then translate to a symbolic form more suitable for mathematical procedures. Translating between alternative representations is key to success in any technical field. In most applied fields—mathematics, engineering, architecture, and computer programming are good examples—a key activity is to translate the verbally stated requirements of a client to the representational forms of the field, because it is those representational forms that can be more effectively and efficiently operated on to satisfy client requirements (Larkin & Simon, 1987). This notion of translating verbal into more graphic or pictorial KRs is also consistent with research demonstrating the advantages of having students construct graphic organizers or concept maps from text (e.g., Lambiotte, Dansereau, Cross, & Reynolds, 1989; Robinson, 1998).

In addition to using the ability to translate between KRs as the object of measurement, how this response type uses KRs in scoring is of interest. One of the attractions of ME items is that they have no single correct answer. Rather, there can be many—perhaps an infinite number—of correct answers because there are numerous ways to express the same mathematical relationship. For ME, examinee responses always share the same basic KR, a mathematical expression. However, correct responses will almost certainly vary in their surface features. Thus, the scoring challenge is one of *mathematical paraphrase*. For example, in field trials, the following were among the correct responses examinees produced for the preceding problem:

$-1/4x + 9/4$	$(-1 * x + 9)/4$	$-1/4 * x + (9/4)$
$1/4 * (9-x)$	$-x/4 + 9/4$	$(-x +9)/4$
$-.25x + 2.25$	$(9-x)/4$	$2 - 1/4 * (x-1)$

To score answers automatically, each response is compared against a *key expression*, where that key expression can be any paraphrase of a correct answer. The comparison is done by substituting values in the examinee's expression, evaluating it, substituting the same values in the key expression, evaluating it, and subtracting one expression from the other. If the result is repeatedly zero (that is, across many different substitutions), the examinee response is considered to be correct. ME scoring works, then, by manipulating KRs. It does nothing more than compare the contents of the examinee's KR to a representation expressed in the same symbol system, which might differ in its surface configuration but, if the response is right, not in semantics. Although examiners have evaluated answers for value rather than expression for centuries, the capability of manipulating algebraic expressions digitally enables designers to employ open-ended responses as work products in this representational form in large-scale tests.

Bennett et al. (1999) also developed the "generating examples" (GE) response type in which problems present constraints but do not present enough information to determine the answer uniquely, and ask examinees to pose one or more instances that meet those constraints. GE questions thus relax the problem structure, although unlike Simon's (1978) "ill-structured" problems, GE items give enough information to determine whether a posed solution is a member of the universe of correct responses. And, unlike ME, this universe is not composed of only paraphrases but also includes quantitatively different responses.

The following is a sample item:

If n and m are positive integers and $11n - 7m = 1$, what are two different possible sets of values for n and m?

The GE item class overlaps with the ME class. That is, we can pose GE items for which the work product is a constructed algebraic expression. That expression can take many quantitatively different forms and each of those forms can, in turn, have many paraphrases. Neither the paraphrases nor the quantitatively different forms may be completely specifiable in advance.

The GE response type can also accommodate other representational forms including numbers, letter patterns, graphs, or geometric figures (see Bennett, Morley, Quardt, & Rock, 2000). From the perspective of KRs, GE can be used to pose a problem in one representational form (for example, verbal) and collect a response in another (for example, symbolic, numeric, figural). But in contrast to ME, GE scores responses using a KR that differs from the examinee's production. This KR is an executable key—computer code that tests each examinee response against the constraints expressed in the item stem. Thus, the executable key is nothing more than an alternative KR of the problem statement, optimized for use by a computer.

For the sample item, the executable key would essentially check each response to see if it:

- Contained two pairs of values,
- Had a second pair different from the first,
- Had each member of each pair be a positive integer,
- Returned for the first pair a true result when its values are substituted for n and m in the equation, $11n - 7m = 1$, and
- Returned for the second pair a true result when its values are substituted for n and m in the equation, $11n - 7m = 1$.

For this question, then, multiple KRs are in play. The examinee works with verbal and symbolic representations in translating the problem, and then with symbolic and numerical ones in formulating a response. The scoring works with the numerical response and its own logical representation to process that response.

Cisco Network Simulator (CNS) Performance Assessments

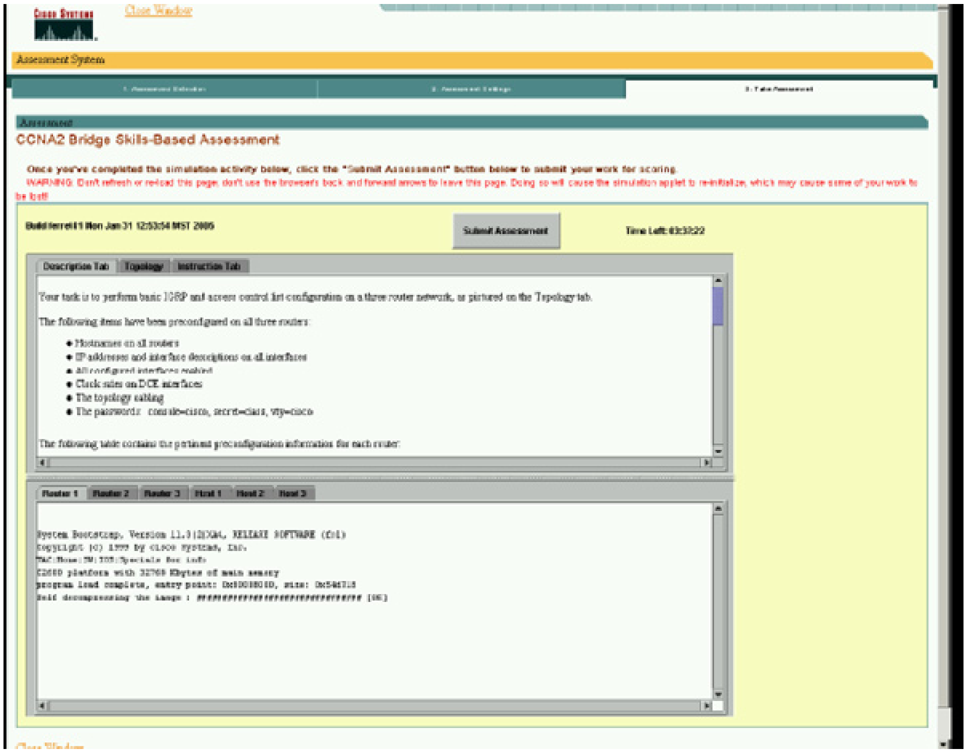
The Cisco Networking Academy Program (CNAP; http://cisco.netacad.net) is a public-private partnership that teaches apprentice-level design, installation, and troubleshooting of computer networks in more than 50,000 locations ("academies") throughout the globe. Since its inception, CNAP has employed hands-on, instructor-administered performance (skills) examinations. When well administered, these exams constitute a "gold standard" for assessing proficiency in the program. With more than 10,000 instructors and little local control, however, their reliability and validity can vary substantially from one site to another. The web-based CNS provides all academies with high-quality simulation-based performance assessment to complement local hands-on exams (Frezzo & Stanley, 2005). The CNS tasks discussed in the following sections grew out of research of the NetPass project (Behrens et al., 2004, Williamson et al., 2004), which produced the initial versions of the presentation process and automated scoring procedures. This section considers the roles of KRs in the development and use of CNS tasks. The interpenetrating roles of technology, cognition, and assessment design theory are clear throughout the discussion.

The CNS Assessment as a Knowledge Representation

The CNS assessment is itself a KR, which coordinates information about the curriculum and instruction that occurs in the Cisco Networking Academy Program, expert-novice studies on design and troubleshooting (Williamson et al., 2004), and research on assessment design in order to provide evidence about student proficiency at the end of the program. Figure 10 shows the web page that the students taking the CNS exam see as they work. This page contains a title, instructions for submitting the assessment, a timer, and tabs that link to key domain KRs that will be discussed further in the following section. The affordances that appear on the web page were designed to mirror other tools that students have used, including real networking devices.

The "assessment as knowledge representation" of CNS is of paramount importance in CNAP. The widely varying quality of skills assessments across thousands of academies meant that instructional goals and performance expectations were not being clearly communicated to instructors and students. CNS was seen as a cost-effective way to use technology to provide this information widely, and to provide students with opportunities to work through the cognitive aspects of design, configurations, and troubleshooting with CNS learning tasks as well as summative exams.

Figure 10: The CNS Examinee Interface



CCNA2 Bridge Skills-Based Assessment

Once you've completed the simulation activity below, click the "Submit Assessment" button below to submit your work for scoring.

WARNING: Don't refresh or reload this page, don't use the browser's back and forward arrows to leave this page. Doing so will cause the simulation applet to re-initialize, which may cause some of your work to be lost!

Build ferrell1 Mon Jan 31 12:53:54 MST 2005

Time Left: 03:33:22

Your task is to perform basic IGRP and access control list configuration on a three router network, as pictured on the Topology tab.

The following items have been preconfigured on all three routers:

- Hostnames on all routers
- IP addresses and interface descriptions on all interfaces
- All configured interfaces enabled
- Clock rates on DCE interfaces
- The topology cabling
- The passwords: console=cisco, secret=class, vty=cisco

The following table contains the pertinent preconfiguration information for each router:

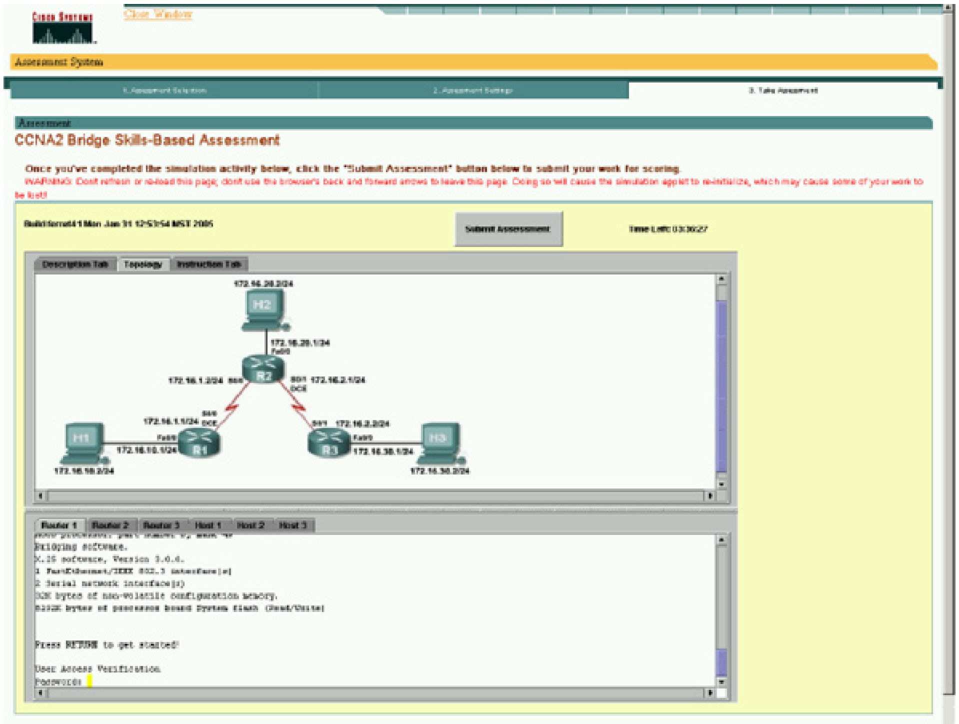
```
System Bootstrap, Version 11.3(2)XA4, RELEASE SOFTWARE (fc1)
Copyright (c) 1999 by cisco Systems, Inc.
TAC:Home:SW:IOS:Specials for info
C2600 platform with 32768 Kbytes of main memory
program load complete, entry point: 0x80008000, size: 0x546718
Self decompressing the image : ################################ [OK]
```

Domain Analysis of KRs in Networking

Subject matter experts analyzed CNAP curriculum materials to survey the KRs used in instructional materials and in real-world problems at the targeted level of skills. They found usage of both general-purpose KRs, such as tables and graphs, populated with networking information and KRs that were particular to the domain.

One example of a critical domain KR in the domain of computer networking, and thus for CNS, is the logical topology representation. The logical topology is an abstracted map of the networking device nodes and the interconnections between those nodes (Frezzo & Stanley, 2005). Figure 11 shows an example of a logical topology, with icons representing PCs and icons representing routers. Two other domain KRs are shown at the bottom of this figure: the command-line interface (CLI), which allows students to interact with the virtual routers, and Cisco's Internetwork Operating System (IOS), which is the control and programming language for networking the switches and routers in the logical topology KR. Both are inherently interactive and technology-based as people use them in actual practice, and as examinees need to use them in CNS tasks. As an aspect of knowledge about the domain, students are expected to be able to understand each type of KR and how the representations interact to describe a given network—that is, what each representation tells one about the network and what it does not, where the representations share information in different forms and must therefore be consistent, and how each representation supports different aspects of reasoning about the network when troubleshooting.

Figure 11: Two Key Domain KRs, the Logical Topology (top) and the Cisco IOS Command-line Interface (CLI) (bottom)



CCNA2 Bridge Skills-Based Assessment

Once you've completed the simulation activity below, click the "Submit Assessment" button below to submit your work for scoring.
WARNING: Don't refresh or re-load this page; don't use the browser's back and forward arrows to leave this page. Doing so will cause the simulation applet to re-initialize, which may cause some of your work to be lost!

Build:format4.1 Mon Jan 31 12:57:54 MST 2005

Time Left: 03:36:27

```
Bridging software.
X.25 software, Version 3.0.0.
1 FastEthernet/IEEE 802.3 interface(s)
2 Serial network interface(s)
32K bytes of non-volatile configuration memory.
8192K bytes of processor board System flash (Read/Write)


Press RETURN to get started!

User Access Verification
Password:
```

Structuring Tasks around Domain KRs

KRs play a central role in assessment in determining the context in which students will provide evidence of their knowledge, skills, and abilities, which includes knowledge and proficiencies with domain KRs. CNS network configuration tasks illustrate the interactions between a student and the delivery system in the presentation, creation, and transformation of KRs.

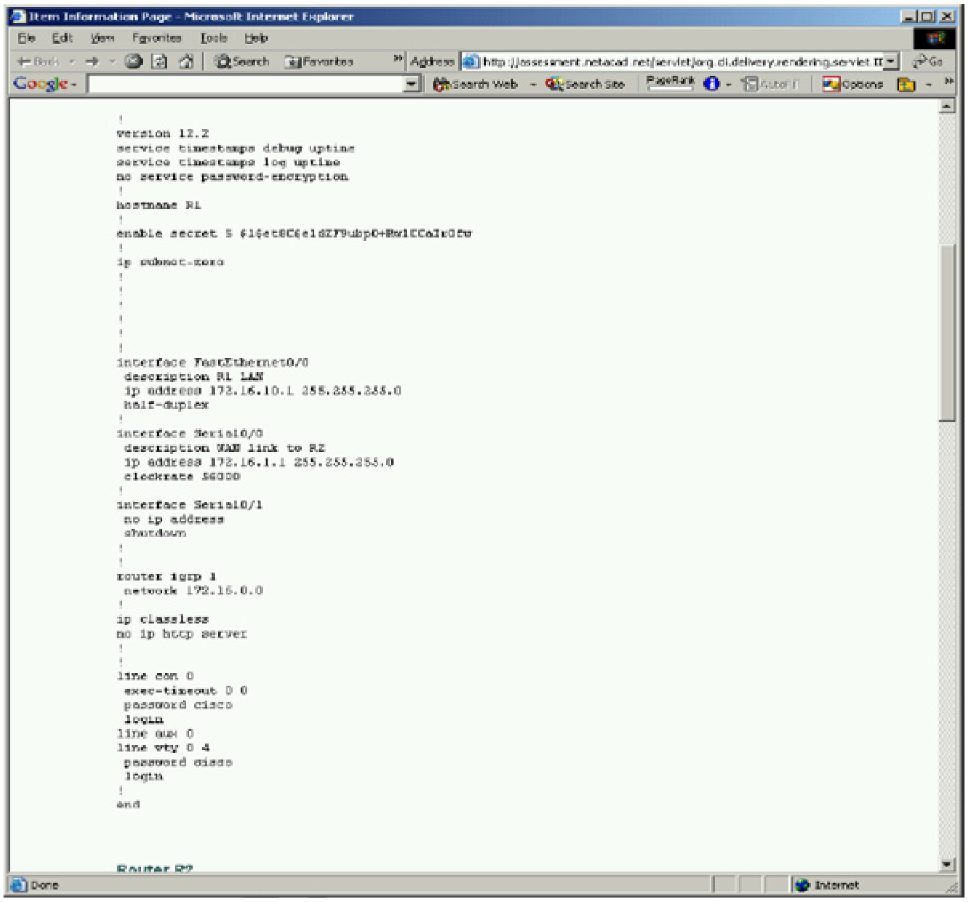
The initial presentation of the problem to the student takes the form of domain KRs, in the form of verbal descriptions using networking terminology and concepts (Figure 10, previous page)), a logical topology diagram (upper window in Figure 11), and a CLI for configuring the devices in the network (lower window in Figure 11). The student uses the CLI to configure the network devices by means of the Cisco IOS control language, which is a symbol-system KR through which humans and network devices communicate with other devices. We note the fidelity of the CNS configuration tasks to real-world device configuration: The CNS environment uses the same Cisco IOS language and the same CLI interface as when configuring real devices remotely from a terminal, and the simulator provides the same messages back as real devices would. This correspondence, made possible by the simulation environment, supports the construct-representation line of argumentation for the validity of these tasks (Embretson, 1983).

As the student proceeds, two new KRs are created and others are transformed. The KRs that are *transformed* are the representations of the devices inside the simulator. These are symbol system KRs as well, representing the state of each hypothetical network device in a digital form that the simulation program can use to compute device responses to communicate back to the student or to modify the behavior of other devices. These are not KRs of the learning domain, but rather of the simulation domain used in the presentation and evidence identification processes in the assessment delivery system. They are optimized to support the processes of the delivery system for presentation and scoring, and are not visible to the student.

The KRs that are *created* are called the running configuration and the log file. The running configuration file for a router is the result of using the CLI to issue commands to change the active configuration of the router and its traffic control behavior. Figure 12 (next page) shows an example. Running configuration files are of great importance in the networking domain, and serve as the key work product in CNS configuration tasks. As a work product, a running configuration file indicates the final status of the network when a student completes the problem. The log file additionally captures all the commands that a student issues during the course of the work and the responses from the network.

Running configuration files and log files are domain KRs, produced by examinees as they interact with a (simulated) network system using the Cisco IOS symbol-system that they are learning for just this purpose. As work products, they are assessment KRs that can be operated on by the evidence identification process of the CNS delivery system to identify and evaluate evidence about student proficiency. The interplay between humans—students and instructors—and the CNS system continues in the automated scoring and reported processes discussed in a later section of this paper.

Figure 12: Router Running Configuration File Serves as a Student Work Product


Item Information Page - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Search Favorites Address http://assessment.netacad.net/servlet/org.di.delivery.rendering.servlet.II Go
Google - Search Web Search Site PageRank AutoFill Options
Done
Internet

```
!
version 12.2
service timestamps debug uptime
service timestamps log uptime
no service password-encryption
!
hostname R1
!
enable secret 5 $1$et8C$e1dZF9ubpO+Rw1ECaIrOfw
!
ip subnet-zero
!
!
!
!
!
!
interface FastEthernet0/0
 description R1 LAN
 ip address 172.16.10.1 255.255.255.0
 half-duplex
!
interface Serial0/0
 description WAN link to R2
 ip address 172.16.1.1 255.255.255.0
 clockrate 56000
!
interface Serial0/1
 no ip address
 shutdown
!
!
router igrp 1
 network 172.16.0.0
!
ip classless
no ip http server
!
!
line con 0
 exec-timeout 0 0
 password cisco
 login
line aux 0
line vty 0 4
 password cisco
 login
!
end


Router R2
```

Using Design KRs to Support Task Creation

Another way in which KRs played a crucial role in the development of the CNS is through the design KRs called design patterns, noted earlier. In the case of CNS, design patterns were used to create multiple forms to ensure exam security. Design patterns that are of interest to the CNS are those related to network design, implementation, and troubleshooting tasks (Wise, 2005). More-focused design patterns were developed from the Problem-Solving in a Finite System design pattern presented earlier, which incorporated the specialized domain knowledge and context of troubleshooting computer networks.

Task shells are another KR used in CNS. CNS task shells are built around the specification of stimulus domain KRs, key aspects of their contents in terms of task model variables, and targeted KRs in terms of work products. Figure 13 is an example of the part of a task shell that test developers use to create instances from a family of simple network design tasks.

Figure 13: **Shell for CNS Design Task Problem Statement. Boldface Phrases are Variables**

1. *Setting sentence*: A(n) **setting** is [create something that is a typical activity for this setting].
2. *Building size sentence*: The **setting** is **buildingLength** long.
3. *Network type sentence*: The **setting** has been asked to install a(n) **EthernetStandard** network for this [the typical activity for this setting created above].
4. *Subgroup 1 specification*: The **subgroup1** connections require a bandwidth of **bandwidthForASubgroup1**.
5. *Subgroup 2 specification*: The **subgroup2** connections require a bandwidth of **bandwidthForASubgroup2**.
6. *Subgroup 3 specification*: The **subgroup3** connections require a bandwidth of **bandwidthForASubgroup3**.
7. *"Force closets" sentence?*: No networking equipment can be stored in the **Subgroups123** area.
8. *Location of POP sentence*: The link to the Internet is located **locationOfExternalConnection(POP)**.

Using KRs to Create Tasks and Manage Assessment Systems

CNS has revolutionized assessment in the Cisco Networking Academy Program, and in turn teaching and learning, by making high-fidelity simulations of the cognitive aspects of the domain available at low cost throughout the program over the Internet. Obviously, the KRs transmitted over the Internet to and from the examinee, in terms of stimulus conditions, interactions with the simulated network, and work products, must be represented in digital form, and transformations from one form to another are necessary to communicate between people and computer processes, and between one process and another.

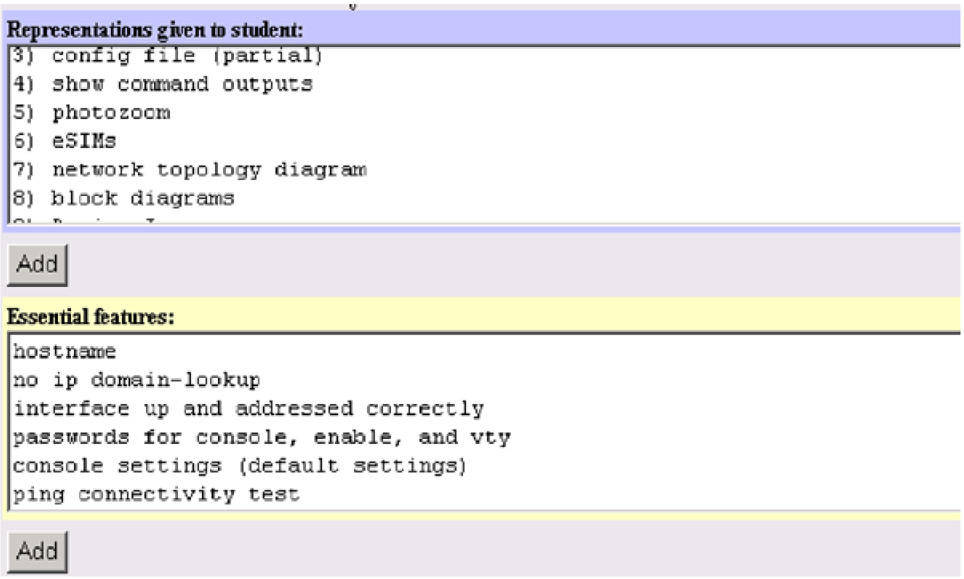
Many domain KRs and design KRs, some of which are mentioned in the previous sections, are used in the design, implementation, and delivery of CNS tasks. In this section we point to two particular ways that KRs are used in computer-supported task design and computer-based delivery—

namely, task authoring and automated scoring. These leverage points concern the way that assessment designs can use technology to more efficiently create the domain KRs examinees interact with, and capture and evaluate the KRs they produce.

As noted earlier, task shells like those used in CNS are not a new idea. They are a KR that has been used for decades to synthesize knowledge in learning domains and knowledge about assessment, to improve efficiency and validity. What is new is the expression of task shells in computer-based forms that facilitate the work of test developers by allowing them to work with interfaces that create task specification KRs and automated or semi-automated procedures that operate on these forms to generate the KRs used in assessment delivery. Figure 14 (next page), for example, shows a screen from a CNS task authoring tool in which a test developer selects stimulus and work product KRs for troubleshooting tasks. Having specified that a topology diagram will be present in a task, the test developer then specifies and configures a network that meets the conditions indicated in the task model variables, using an interface similar to the one that a student uses in a design task. The output of this interaction is another KR, an XML file whose format can be used by the presentation process to display the topology diagram, and by the simulator to create the network and govern its behavior.

CNS uses automated scoring procedures in the evidence identification process. They consist of computer programs that scan for salient features of the KRs produced by students' interactions with the presentation process, namely configuration files, log files, and network topology XML files. The scoring rules for the running configuration in configuration tasks, for example, produce values for graded response observable variables for accuracy of the routing protocol, whether access control lists (ACLs) are assigned to appropriate devices, and the correctness of the ACL rules. Log files contain more information—for example, about strategy use and efficiency—but these would present greater scoring challenges because they can vary considerably from one student to another. The NetPass prototype used logical rules to identify the presence or absence of key features of the interaction, systematicity of steps, and number and seriousness of errors (Williamson et al., 2004). Clauser et al. (1997) describe this style of automated scoring for interactive problem solving in simulated patient-management problems at the National Board of Medical Examiners. Viewing the interaction between an engineer and a network as a conversation carried out in the Cisco IOS language, DeMark and Behrens (2004) took a statistical language processing approach to analyzing the log files, with promising results in classifying learners along a novice-to-expert curriculum.

Figure 14: Screen from CNS Task Authoring Interface



Representations given to student:

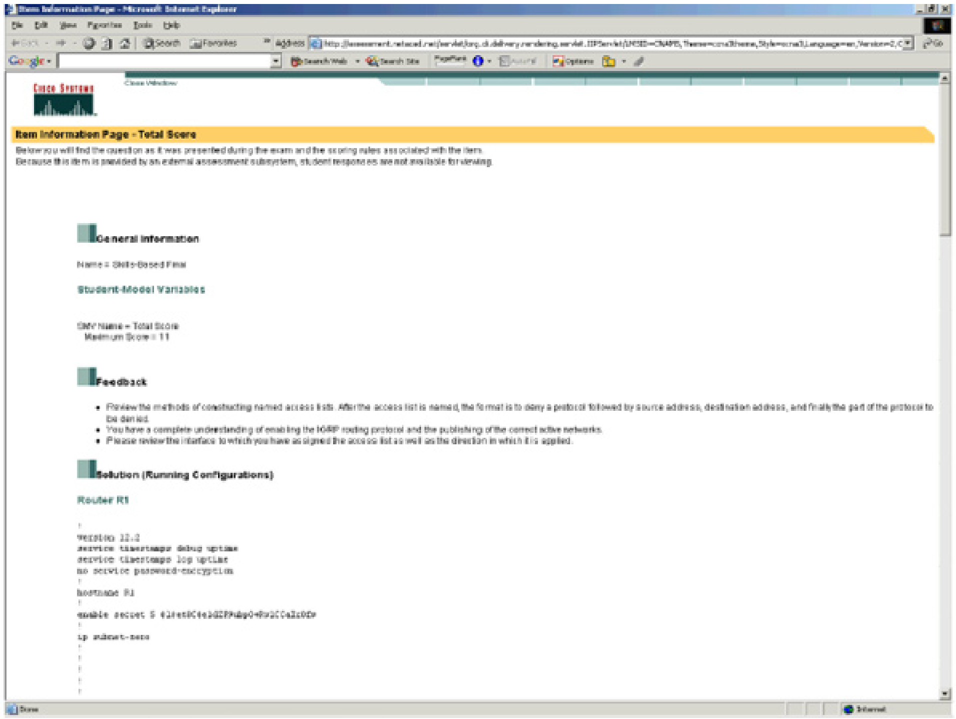
3) config file (partial)
4) show command outputs
5) photozoom
6) eSIMs
7) network topology diagram
8) block diagrams

Essential features:

hostname
no ip domain-lookup
interface up and addressed correctly
passwords for console, enable, and vty
console settings (default settings)
ping connectivity test

The resulting observable variables are a KR that is sent the reporting process to produce the student score report. A computer program thus transforms information in the form of machine-readable KRs containing values of observables into a KR that summarizes results on this task for human students and instructors. The reporting process creates an accompanying KR called an item-information page (Figure 15, next page), which details by item how the student responded and the scoring rubric that was applied.

Figure 15: **Item Information Page Including Student Model Variables, Feedback, and Work Product**



Item Information Page - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Search Favorites Address
http://assessment.netacad.net/servlet/org.cli.delivery.rendering.servlet.IIPServlet/LMSID=CNAMS,Theme=ccna3theme,Style=ccna3,Language=en,Version=2,C
Go
Google Search Web Search Site PageRank Options
Close Window
Cisco Systems
Done
Internet

Item Information Page - Total Score

Below you will find the question as it was presented during the exam and the scoring rules associated with the item.
Because this item is provided by an external assessment subsystem, student responses are not available for viewing.

General Information

Name = Skills-Based Final

Student-Model Variables

SMV Name = Total Score
  Maximum Score = 11

Feedback

- Review the methods of constructing named access lists. After the access list is named, the format is to deny a protocol followed by source address, destination address, and finally the part of the protocol to be denied.
- You have a complete understanding of enabling the IGRP routing protocol and the publishing of the correct active networks.
- Please review the interface to which you have assigned the access list as well as the direction in which it is applied.

Solution (Running Configurations)

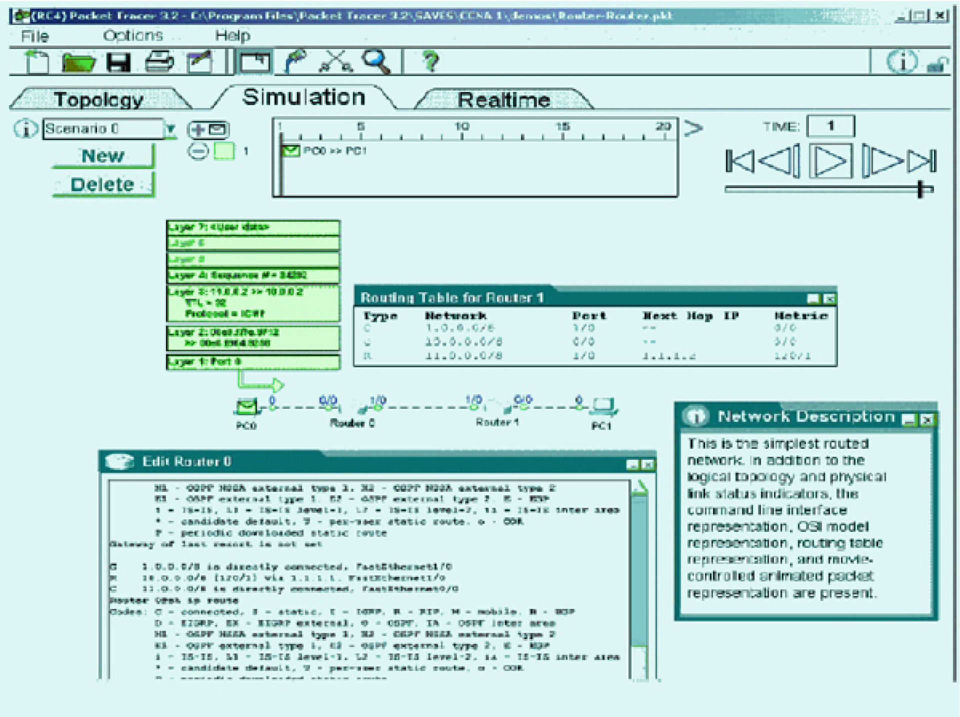
Router R1

```
!
version 12.2
service timestamps debug uptime
service timestamps log uptime
no service password-encryption
!
hostname R1
!
enable secret 5 [illegible]
!
ip subnet-zero
!
!
!
!
!
```

KRs play roles in managing and coordinating the various aspects of building an assessment. For CNS, aspects of the curriculum, instruction, and assessment are intertwined around the domain and design KRs. Many actors, including learners, instructors, subject-matter experts, programmers, psychometricians, and automated delivery processes use the KRs that are embodied in the assessment to interact and communicate with one another. Several benefits have accrued from explicating and exploiting the roles of KRs in assessment design (DeMark, West, & Behrens, 2005). These include improving alignment among curriculum, assessment, and instruction; providing efficiency and scalability in task and test construction; and grounding the defensibility of tasks in high-stakes tests.

In more recent work, assessment designers have extended these ideas to more local customization for instructors for learning exercises and formative assessment. A dynamic software environment called Packet Tracer allows instructors to create tasks and students to use and manipulate the multiple KRs it contains (Frezzo, 2009; Frezzo, Behrens, & Mislevy, 2009). Figure 16 (next page) shows an example with multiple interactive KRs, including the logical topology and command-line interface. The central development team used design patterns for network design, configuration, and troubleshooting to create sample tasks and a help system to assist instructors in using Packet Tracer effectively.

Figure 16: Packet Tracer's Multiple Interactive KRs, Including Logical Topology, Cisco IOS CLI, OSI Model View, Router State Table, and Animated "Packet Movie" Mode



Layer 7: <User data>
Layer 6
Layer 5
Layer 4: Sequence # = 34292
Layer 3: 11.0.0.2 >> 10.0.0.2
TTL = 32
Protocol = ICMP
Layer 2: 00e0.f7fe.9f12
>> 00e0.f9b4.9258
Layer 1: Port 0

Routing Table for Router 1

Type	Network	Port	Next Hop IP	Metric
C	1.0.0.0/8	1/0	--	0/0
C	10.0.0.0/8	0/0	--	0/0
R	11.0.0.0/8	1/0	1.1.1.2	120/1

```
       N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
       E1 - OSPF external type 1, E2 - OSPF external type 2, E - EGP
       i - IS-IS, L1 - IS-IS level-1, L2 - IS-IS level-2, ia - IS-IS inter area
       * - candidate default, U - per-user static route, o - ODR
       P - periodic downloaded static route
Gateway of last resort is not set

C    1.0.0.0/8 is directly connected, FastEthernet1/0
R    10.0.0.0/8 [120/1] via 1.1.1.1, FastEthernet1/0
C    11.0.0.0/8 is directly connected, FastEthernet0/0
Router Show ip route
Codes: C - connected, S - static, I - IGRP, R - RIP, M - mobile, B - BGP
       D - EIGRP, EX - EIGRP external, O - OSPF, IA - OSPF inter area
       N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
       E1 - OSPF external type 1, E2 - OSPF external type 2, E - EGP
       i - IS-IS, L1 - IS-IS level-1, L2 - IS-IS level-2, ia - IS-IS inter area
       * - candidate default, U - per-user static route, o - ODR
```

This is the simplest routed network. In addition to the logical topology and physical link status indicators, the command line interface representation, OSI model representation, routing table representation, and movie-controlled animated packet representation are present.

Conclusion

These are exciting times in assessment, with rapid developments in fields that are fundamental to the conception, design, and use of educational tests. These include statistics, measurement models, technology, cognitive psychology, and learning domains. The challenge is how to put new insights to work to improve assessment. Knowledge representation plays a central role in this endeavor. Two primary ways in which external KRs play a role in assessment can be described as domain KRs and design KRs.

Domain KRs are representations that are used to express ideas and to carry out work in domains. They concern *the what* of assessment. Insights from the cognitive, situative, and sociocultural perspectives in psychology help us to understand the roles of KRs in the development of competence and of expertise. They are critical for understanding the domain; hence they are pivotal points in learning and in assessment. Learning to think in their terms is a target of learning; they are used in assessment to help define the environments that students work in and to serve as vehicles for carrying out the work, and as they are produced, they constitute work products for evaluation. Continual advances in technology mean that KRs are increasingly interactive and amenable to digital representations. It is through the psychology of using KRs and the theory of assessment design that we will understand how to present information, afford interaction, and capture work products in these forms.

Making assessment design more efficient requires greater understanding of the assessment enterprise. Recent work on "assessment engineering" (e.g., Luecht, 2002; Mislevy et al., 2003) aims not only to make the underlying principles explicit, but also to embed the underlying principles in design KRs that help assessment professionals structure, and at times automate, their work (Mislevy & Haertel, 2006). Assessment design KRs thus concern the *how* of assessment. They facilitate communication between different levels of the assessment design and provide capacity for reusing assessment ideas and task components. Advances in technology equally provide opportunities to design and deliver assessments more effectively. It is through improved frameworks of assessment design that we will understand how to create design KRs to capitalize on these opportunities.

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Author Biographies

Robert J. Mislevy is a Professor in the Department of Measurement, Statistics, and Evaluation (EDMS) at the University of Maryland at College Park. His research applies developments in statistics, technology, and cognitive research to practical problems in educational assessment. He can be reached at rmislevy@umd.edu.

John T. Behrens is Director, Networking Academy Learning Systems Development at Cisco, and Assistant Adjunct Research Professor in the Department of Psychology at the University of Notre Dame. His research concerns the intersection of psychological, computational, and statistical methods applied to the development and evaluation of on-line learning and assessment. He can be reached at jbehrens@cisco.com.

Randy Bennett is Distinguished Scientist in the Research and Development Division of Educational Testing Service in Princeton, NJ. His research focuses on integrating advances in cognitive science, measurement, and technology to create new approaches to assessment at the K–12 level. He can be reached at rbennett@ets.org.

Sarah DeMark is Senior Manager of the Expert Certifications group at Cisco Systems. She is focused on applying cognitive and measurement research to high-stakes assessments. She can be reached at sdemark@cisco.com.

Dennis C. Frezzo, Ph.D, is a Senior Manager in the Cisco Network Academy Learning Systems Development Group. His team performs research and development in the areas of interaction design, networking simulations, educational games, networking domain pedagogical content knowledge, and networking instructor communities of practice. He can be reached at dfrezzo@cisco.com.

Roy Levy is an Assistant Professor in the Division of Learning, Technology and Psychology in Education at Arizona State University. His interests include psychometric and latent variable modeling for educational and psychological assessment and social science research. He can be reached at Roy.Levy@asu.edu.

Daniel H. Robinson is a Professor in the Department of Educational Psychology at the University of Texas. His research examines the impact of educational innovations on learning and motivation. He can be reached at dan.robinson@mail.utexas.edu.

Daisy Rutstein is a doctoral candidate in the Measurement, Statistics and Evaluation department at the University of Maryland, College Park. Her current research interest include Bayesian Inference Networks and Assessment Design. She can be reached at dawise@umd.edu.

Valerie J. Shute is an Associate Professor in the Department of Educational Psychology at Florida State University. Her general research interests hover around the design, development, and evaluation of advanced systems. Current research involves using games and stealth assessment to support learning of 21st century skills. She can be reached at vshute@fsu.edu.

Ken Stanley is a Learning and Development Manager at Cisco Systems. His primary responsibilities include media development for new courses and assessment development using complex simulations. He can be reached at kestanle@cisco.com.

Fielding I. Winters is a postdoctoral researcher and instructor in the Department of Human Development at the University of Maryland at College Park. Her research areas include peer collaboration, self-regulated learning, and epistemic cognition. She can reached at fwinters@umd.edu.

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Caroline A. & Peter S. Lynch School of Education, Boston College