Guidelines for Modular Design

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1.0 Introduction

VaNTH's vision for improving engineering education includes creating new instructional approach based on principles of Learning Science. The ulitamate goal is to create a new *learning environment* to optimize the learning experience for all bioengineering students. Therefore, the domain groups have been given the challenge of integrating learning science principles into their courses in a "modular" perspective. This leads to many interesting questions including,

What is a module ?
What is the unit size of a module?
How is a module created?
What should a module cover and how long should it take?
How should the content be organized to help students learn with understanding?

As designer of a course, what issues would you consider to be the most critical.

One of the goals of this report is to define a method for developing a "modular" version of a course that can be easily shared and used by others. The aim is to build on what is currently used for a course and refine it using principles of How People Learn (HPL) (see HPL framework, book at http://www.nap.edu/html/howpeople1/ (see chapter 6 Design of Learning Environments) and a tutorial at http://extend.ltc.vanderbilt.edu/module/HPLmini/). Further, the aim is to enhance the learning experience for the students without increasing the workload of the professor. In fact, the process of modularizing a course offers interesting opportunities to improve instruction. A course using a modular design divides up its content into learning activities that target specific concepts germane to that domain. Based on cognitive research, one effective instructional method is to anchor specific domain content around challenges that exemplify the utility of that content. The challenges will be the entry point into a series of *learning activities* designed to help students explore the concepts related to that challenge. This combination of challenges and learning activities is called a "module".

Modules are designed by systematically linking learning resources, or granules, together based on pedagogical principles defined by current learning theory. Granules are small resources, like movies, sound files, text descriptions, urls, simulations, power point slides etc. These resources can be used in a variety of different learning settings depending on the targeted concepts of a particular module. The HPL framework provides principles for making decisions on how to link these granules together to help students build their understanding of the domain. The instructional process help students build a conceptual model of the domain so they understand how the various pieces fit together. Designing a course using this modular approach requires a clear definition of the learning objectives for the courses, and careful organization of the instruction to optimize student learning. The following paper explores one method for converting a course outline of learning objectives into a "*challenge based*" learning environment.

There are several major objectives of this report including: 1) defining and prioritizing the content and skills from the domain taxonomy that the course should cover, 2) define learning objectives for what students should be able to do at the end of the course which demonstrates their "understanding", and 3) identify and sequence learning activities that develop this level of "understanding". The first section describes an activity designed to establish course objective and challenges that can be used for modules. The second half of the report focuses on designing Challenge Based modules using the "How People Learn Framework".

2. Establishing course objectives from the taxonomy

Every design plan begins by establishing a clear set of goals. For instruction, we need to clearly define what students should know and be able to do at the end of a course. Therefore, the course objects should include a statement of the *desired outcomes* of the course, which include the fundamental principles of the domain and how they are applied. For example, a course in introductory biomechanics could focus on developing students' ability to analyze forces applied to a "biological system", where the "biological system" could be the muscular skeletal system, the muscle fibers or blood cells traveling through the vascular system. Investigating the analysis of these systems requires students to learn how to apply principles of classical physics (statics and dynamics), geometry, algebra, anthropometrics and anatomy, to name a few.

A course list of desired outcomes emerge from the large list of content and skills defined by the taxonomy of the domain. Therefore, the first step is to determine which of these concepts from the taxonomy are critical to learn in the specific course and how they relate to the major learning objective(s).

In addition, it is important to identify critical skills necessary to achieve the overarching goals of the course. In the biomechanics example this might include being able to isolate the relevant system for analysis (e.g. external forces on the body versus internal forces generated by muscles), using Free Body Diagrams, vector analysis and recognize the mechanical properties related to joints, muscles, bones and ligaments. Creating a high level outline of these major principles and skill sets will identify the major content areas, or meta categories, that modules need to target. This following activity is one method for identifying critical concepts and skills students should know and demonstrate.

Once we have these categories we can identify challenges that target these learning objectives and content areas. The final step is to apply the principles of How People Learn Framework to describe a series of learning activities that will promote learning with understanding.

2.1 Activity 1 – Identify the major learning objectives of your course

This activity is designed to identify the critical characteristics of a domain that students need to understanding to apply this knowledge to future problems. Use this opportunity to identify and record your implicit and explicit goals for the course. The information generated in this activity will assist in identifying interesting challenges to use for instruction, prioritize the time spent on a domain topic, and indicate how to assess students' understanding.

STEP 1 – Identify the major concepts to be explored in the course

One of the critical steps in building a course is to identify the major learning outcomes for your students to be able to demonstrate at the end of your course. One place to begin is to highlight the key concepts of the domain ***taxonomy*** to identify what content students should know relative to the major objectives for the course. Then turn these domain categories into specific outcomes relevant to the grade and focus for the course. For example, in biomechanics a major learning outcome could be "every student can analyze the forces on the human body in both static and dynamic situations." This will require students to apply the laws of physics and mechanical properties they've learned in prior courses to a biological system. This one goal of learning to analyze the forces on a human body can incorporate ***taxonomic*** categories including 1) the fundamental principles of physics and mathematics, 2) the muscular skeletal system, anatomy and physiological systems of the body 3) dynamics and 4) strength of materials (both biological and those that the body interacts with). Then expand these categories into a more detailed list of concepts defined in the domain taxonomy. This list of concepts should represent the critical content students should know and be aware of to achieve the major course objectives.

Table 1 – Concepts and Skills for Introductory Biomechanics

FUNDAMENTALS
units
vector analysis, vector components, vector products
forces
moments, couples
equivalent force systems, resultant force systems
composite body center of gravity, center of mass
centroid, distributed body centroid, distributed load
MUSCULOSKELETAL SYSTEM AND STATICS
levers, musculoskeletal machines
bone, joints, tendon, ligament, muscle
equilibrium, free body diagrams
types of support
2 force and 3 force system statics, method of sections
equilibrium analysis - upper extremities
equilibrium analysis - lower extremities
DYNAMICS
linear kinematics, linear kinetics
angular kinematics, angular kinetics

impulse-momentum methods
area and mass moments of inertia, moment of impulse
dynamics of limb movement

STRENGTH OF MATERIALS

deformation, stress and strain
material properties, Hooke's law, axial loading
bending - shear and moment diagrams
bending - normal stress, bending - shear stresses
stress concentration
statistically indeterminate systems, torsion indeterminate systems, torsion

STEP 2 – Establish Learning Objectives from Taxonomy categories

The next step is to transform this list of concepts into actions that students can perform to demonstrate their level of understanding expected by the instructor. List out concepts and skills associated with these big ideas that are appropriate to the level of students to be taught. Also, indicate what students should be able to do with these concepts and skills. Try to use action words like, calculate, define, explain, notice, identify difference between, etc. Table 2 is a partial list for Biomechanics. Table 2 illustrates how a course outline, like table 1, can be detailed into a list of learning objectives.

STEP 3 – Prioritizing the content

The goal of this step is to identify how critical this content is toward achieving the major learning outcome for the course. This could be done by using a numerical scale from say 1 to 5, where 5 is a key concept that needs to be explored in-depth and 1 is worth mentioning, but won't keep students from achieving the major outcomes. Alternatively, Wiggins and McTighe (1998) suggest categorizing the content into three levels to identify how fundamental these concepts are to the goals of the course. These levels include:

Essential - these concepts are fundamental to the domain and the major objectives,
Important - concepts students should be able to recognize and use, but not necessarily fluent,
Familiar - are concepts students should be aware of, but if they don't now it, then it won't limit their problem solving process of common problem.

Try to use these categories to prioritize which concepts require the most coverage. One method for organizing this step is to make the course outline the first column of a spreadsheet table as in Table 2. The second column could be the level of importance for these concepts.[1]

STEP 4 – Designing Challenges for Instruction

Students often ask the questions "Why do I need to know this?" When the content is presented as a list of abstract ideas, they often fail to notice the connection between the ideas. Therefore, one of the major goals of instruction is to help students make links between the ideas. Context or situations that demonstrated these links between domain concepts are excellent methods to help students build a model of the domain and how it functions. Starting with a challenge provides a goal for what students are trying to achieve as part of their studies. You can create a kind of "road map" for how students will explore various topics in an effort to understand the solution to this larger challenge. This definition, or road map, of the goal state help students create a vision of where they are heading and helps them monitor their progress toward this goal. They can continually ask themselves if they know how to apply what they are learning to this end goal.

[1] Ultimately, this classification of the objectives will help define which concepts should be covered in-depth and which concepts students only need to be familiar with. This list could help future instructors know more about what students have covered and to what degree.

The motivation for each module emerges from the complexity of the challenges that exemplify the desired concepts to be learned. Therefore, the modules need interesting challenges that engage students in a process of inquiry that requires them to apply the desired concepts beyond simple manipulation of the mathematics.

The next step is to identify interesting challenges that target this domain knowledge. The columns in Table 2 can be expanded one for each new challenge. The cells in each column can represent how the concepts relate to the specific challenge (High, Medium, or Low). Through this process we can begin to see which content is covered and to what degree. Then, we can match this level of coverage with the overall ranking used to establish the priority of the content. Any disparity between the coverage and the priority rating from Step 3 should be an indicator of mismatched priorities.

<u>Example challenge</u>

One example of a challenge for the introductory biomechanics course could review the general principles of physics and geometry as they apply to an athlete using equipment, such as a gymnast on rings or parallel bars, or performing floor exercises like a handstand. An athlete performing a feat of strength by maintaining an iron cross position could lead to a range of investigations that students can explore including –

What are the strength requirements of the cables and rings to ensure the safety of the athlete?
What muscles provide most of the strength and stability?
What forces are exerted on the bones?
Where is the athlete most susceptible to injury in this position?

Providing challenges like these in class and for homework provides students with the opportunity to explore the content within a context. Also, it requires students to demonstrate their ability to accurately and fluently analyze a system of forces applied in a "biological system". This helps them understand how to apply this knowledge in various situations, rather than learning it as rote facts or only procedural skills.

<u>3. 0 Activity 2 - Designing the instructional sequence of learning activities</u>

Designing instruction requires making several important decisions, including" 1) what sequence of activities will help students notice and apply the fundamental principles of the domain, 2) what should students do on their own and what should be done during class time? And 3) how much should a professor track students' progress toward the major goal of the course? These decisions all relate to defining learning activities that help students generate their own understanding, research information that will develop what they don't know, and refine their understanding of the content. This next activity explores these questions and defines several methods for designing and sequencing learning events to help students' learn with understanding.

The traditional model of instruction makes some basic assumptions about how people learn which we need to understand in order to define a new method. The traditional model for instruction often follows a pattern of 1) students reading materials before class 2) professor lectures in class 3) students apply and practice what they learned by doing homework. In more general terms the process follows a pattern of determining

- How to prepare students for class?
- What students do during class?
- What students do after class?

This may seem obvious, but thinking through and prioritizing the learning activities can be a complicated task. In the past, the only materials available prior to class were textbooks or selected readings. With advances in technology and in learning theories, now we can ask students to view and comment on demonstrations or perform virtual labs, and share their experience using on line tools, all prior to coming to class. Or, we can ask them to explore various topics and generate and share their naive conceptions prior to class. They may not understand everything they see, hear and read; however, if carefully selected and presented, students can engage in the content of the domain in a whole new way. They can explore various concepts and phenomenon before the professor even begins to speak in class. This approach of pre class activities challenges the assumption that students lack any knowledge to attempt a task before the professor provides some background knowledge during lecture. Allowing students to struggle with the content prior to class helps students notice important characteristics of the domain and identify what they don't understand. This can change the whole dynamics of the class time. If students take the time to prepare and reflect on what they understand, then they are more likely to get more out of the class time. They should be prepared to recognize when they are uncertain about something and begin to ask questions in class.

Now, when students come to class the professor can use class time to build on what students have reviewed and explored prior to class. The classroom experience should help them reorganize their thinking to enhance their abilities to perform the post-class session learning activities. In many ways the goal of class time should be viewed as the opportunity for students to interact with the professor to help refine their thinking so they can return to problems they are trying to solve. (Note, that if we have technology or activities that help capture students' level of understanding prior to class, then the professor can more efficiently prepare for class and provide a well-organized presentation of information that targets the naïve conception demonstrated by the majority of students). With the right kind of activities both the teacher and students can identify where they need more help in their quest to understand a new domain.

The next issue is how to use class time effectively. If the pre-class activity is effective, then it will prime students with critical questions they would like to know more about. It may be that a lecture is just what they need to bring ideas together. Or classroom discussions can be used to help students identify what they know and don't know which can lead to increasing their understanding (this has other benefits such as building community). Or small group work can provide a useful mechanism to increase students' engagement and help them learn from each other. The purpose of discussion and group work in class is to have students generate their own thoughts and ideas and try to integrate these ideas into a larger picture, or conceptual model, of the domain. Students need to take this opportunity to ask questions and refine their thinking. If they have worked on the pre-class activities, then they should be prepared to engage in an interactive class session.

After class, additional learning activities need to strengthen students' understanding and extend it to multiple contexts. Therefore, students need to engage in additional post class activities that allow them to display what they know and self assess their progress. The range of homework activities is also obvious including, homework problem sets, essays and reports, projects, preparing presentation. However, the definition of the goals for these projects can often be the difference between a trivial assignment students view as busy work versus a meaningful activity that engages students in thinking about the domain knowledge in various ways. Students need to continually reflect on what they know to help clarify ideas and answer their questions. The next section will discuss a method for organizing and defining activities based on pedagogical principles for designing effective learning environments.

Table 2 - Sample of Detailed Learning Objectives from BME 101 (Roselli, 1999)

BME 101 **Learning Objective**	**Coverage: H=high, M=medium, L=low, blank =N/A**		
	Priority level E=Enduring I=Important F=Familiar	**Mosaic 3: Forces and Biomechnics**	**Module 5 Iron Cross**
Major objectives of Biomechanics Students should be able to -			
Differentiate between the terms "mechanics" and "biomechanics", and how biomechanics relates to bioengineering.	E	M	M
Explain major classifications of mechanics and how various examples relate to applications in biomechanics.	E	M	
Apply principles of basic mechanics to physiological systems	E		
Be aware of how BME 101 fits into the overall BME curriculum.	F		
Body Segment Anthropometry			
Use anthropometrical tables to determine body segment lengths, weights, volumes, densities, mass moment of inertia, and the location of their centers of gravity.	I	M	H
Forces			
Recognize various application of the concept of "force" (e.g., gravitational, electrostatic, friction, buoyant forces) and its relationship to motion and/or deformation. Also, demonstrate how these forces act on a body.	**E**	**H**	**M**
Use vector notation to represent force in internal and external system (e.g. magnitude, direction, line of action, point of application)	**E**	**H**	**M**
Notice (or recognize) and define the major force classifications used in biomechanics:	**F**	**H**	
Identify specific classifications of force systems such as coplanar force systems, collinear force systems, concurrent force systems, and parallel force systems.	**I**	**H**	
Dimensions, Units and Conversions (should be mastered in earlier courses, but very important in this course)			
Define the concept of "fundamental dimensions" and know the fundamental dimensions used in mechanics: length (L), time (T), mass (M) and force (F).	E		
Perform conversions of units used in mechanics for the SI and English systems.	E	H	
Use tables of conversion factors to convert units from the SI to English systems and vice-versa.	E	H	M
Define the meaning of prefixes like "giga" or "nano" and know how they quantitatively modify units.	E	H	M
Fundamental Quantitative Laws and Relationships involving Forces in Mechanics			
Apply Newton's three laws of motion to biological application in terms of mathematical equations.	E	H	M
Apply Newton's Law of Gravitation to find the acceleration due to gravity on a planet, given R, M and G.	F	H	

BME 101 **Learning Objective**	**Coverage: H=high, M=medium, L=low, blank =N/A**		
	Priority level E=Enduring I=Important F=Familiar	**Mosaic 3: Forces and Biomechnics**	**Module 5 Iron Cross**
Compute the weight of any body at the surface of the earth, given its mass (you should know g = 9.81 m/s2 = 32.2ft/s2).	E	H	M
Explain and identify when why we can neglect the force of attraction between two bodies on the earth relative to the weight of either body.	E	H	
Learn how different types of forces are related to other properties in a quantitative fashion:		H	
Vector Properties of Force: Vector Components, Vector Products, Vector Manipulations			
Use a right handed coordinate system to evaluate forces applied to a biological system	E	H	M
Explain the right hand rule convention – that is, what is the difference between FXr and rXF	E	H	M
Demonstrate how vectors components can be combined to determine solution vectors.	E	H	M
Compute the magnitude and direction of a vector, given its components, or the components, given the magnitude and direction.	E	H	M
Find a unit vector in the direction of a given vector.	I	H	
Use direction cosines in appropriate situations and be able to explain why they are applicable for a given situation.	I	H	
Explain how the dot product of two vectors represents the Moment (i.e. the relationship of M=distancexF is the right hand rule and that M=Fxdistance is the left hand rule).	E	H	M
Define the physical meaning of the cross product of two vectors A and B.	E	H	M
Moments and Couples			
Define a couple. Understand that a couple does not have a definite point of application.	E	H	M
Learn the definition of the moment MP (MP = r x F) of a force F about a point P if the position vector from P to anywhere along the line of action of F is r.	I	H	M
Define a moment arm and understand how to use it to compute a moment.	I	H	M
Given a moment MP, find the moment about a line in the direction of a vector v whose line of action passes through P.	F	H	M
Mechanical Equivalence and Resultants of Force Systems			
Define mechanical equivalence of force systems and be able to determine if two systems of forces applied to the same body are mechanically equivalent.	E	H	M
Demonstrate the ability to reduce a system of forces into single resultant forces	I	H	M
Know how to use the vector equations above to find equivalent forces & couples, and resultant forces and couples.	I	H	M

BME 101 **Learning Objective**	**Coverage: H=high, M=medium, L=low, blank =N/A**		
	Priority level E=Enduring I=Important F=Familiar	**Mosaic 3: Forces and Biomechanics**	**Module 5 Iron Cross**
Centroid, Center of Volume, Center of Mass, Center of Gravity			
Find the centroid of an area center of volume, center of mass and center of gravity by integration.	F	H	M
Demonstrate the ability to combine the centroids of individual component to find the equivalent centroid of the system	I	H	M
Distributed Loads			
Find the magnitude and location of a force that is equivalent to a distributed load (q(x), lb/ft) placed on an object.	F	H	M
Musculoskeletal Machines			
Define a machine and the three classifications of machines that can be found in the human body.	F		
Define mechanical advantage for force in a lever system.	F		
Recognize the different classes of lever systems found in the musculoskeletal system and show how to use the principles of each to determine mechanical advantage	F		
Classify a lever system when the forces are not perpendicular to the lever.	F		
Skeletal System			
Explain the major functions of the skeletal system.	E		
Describe the three planes and three axes used in anatomy. Be able to formalate the right representation when used in a problem.	E		
Explain the difference between the axial skeleton and the appendicular skeleton.	F		
Define and know how to use the following anatomical terms: proximal, distal, lateral, medial, superior, inferior, posterior, anterior, dorsal, ventral.	E		
Bone			
Identify the major classifications of bone.	I		
Explain the difference between cancellous (spongy) bone and compact (cortical) bone?	I		
Describe how bone supports both the structure and function	I		
Learn to estimate material properties using computed tomography	F		
Ligaments & Tendons			
Explain how or use of the structure and function of tendons and ligaments as they apply to biomechanical problems (e.g. how does a force on a tendon increase as a joint is bent.)	I		
Articulations			
Explain (recognize?) the three general classifications of joints.	F		M
Define six different types of freely movable (synovial or diarthrodial) joints and learn which of these are uniaxial, biaxial or triaxial.	F		M
Understand the characteristics of freely movable joints.	I		H
Recognize when joints are in and use these terms to describe it: flexion, extension, pronation, supination, abduction, adduction, inversion, eversion, dorsiflexion, plantarflexion.	E		H

BME 101 **Learning Objective**	**Coverage: H=high, M=medium, L=low, blank =N/A**		
	Priority level E=Enduring I=Important F=Familiar	**Mosaic 3: Forces and Biomechnics**	**Module 5 Iron Cross**
Muscle			
Define the general functions of muscle. Explain how muscles achieve motion (at the level of muscle fiber)	E	H	H
Identify the general anatomy and classifications of skeletal muscles, including origin, insertion, agonist, antagonist, muscle groups, uniarticulate, biarticulate, fusiform (longitudinal) muscle, pennate muscle, muscle fibers and muscle fibrils.	E	H	H
Describe the structure and function of the sarcomere and the molecular basis for muscle contraction.	E	H	
Describe how motor units and the basic mechanisms of excitation-contraction coupling.	E	H	
Explain the non linear relation between muscle tension and muscle length for skeletal muscle and relate this to the structure of the sarcomere. Be able to use graphical representation to support claim	I	H	
Learn typical force-velocity relationships for skeletal muscles and relate them to human activity.	F	H	
Recognize how fiber recruitment and muscle recruitment influence the tension that is developed in skeletal muscles and muscle groups.	E	H	H
Estimate the magnitude and the line of action of the force generated by a skeletal muscle or muscle group.	I	H	H
Computer rotary, stabilizing, and dislocating components of muscle force.	I	H	H

3.1 Organizing instruction using STAR.Legacy.

The endeavor of designing modules requires creating a set of learning activities that help students' inquiry around challenges identified in the objectives matrix created in Activity 1. Organizing the content around interesting challenges provides students with the opportunity to enhance their problem solving and inquiry skills while exploring new content. However, using complex challenges for instruction requires a systematic approach for helping students sustain their inquiry as they explore potential solutions. One method for determining what to do and when to do it is to organize instruction using a template called STAR.Legacy, often referred to as Legacy. The structure of Legacy is founded on the principles of the How People Learn (HPL) Framework. The HPL Framework focuses attention on four dimensions that can be used to assess the effectiveness of learning environments. These include the degree to which environments are knowledge centered (in the sense of teaching for understanding in a way that supports transfer), learner centered, assessment centered (especially opportunities for formative assessment, feedback and revision) and community centered. The challenge for designing an effective atmosphere for learning requires a balance among these dimensions. The Legacy framework provides a structure that guides a designer of instruction as they plan their module. In addition, the framework also guides students systematically explore potential solutions to a specific challenge.

The Legacy framework uses a "***learning cycle***" (based on an inquiry cycle) to define critical phases of exploring a complex challenge. Figure 1 is a visual representation of the learning cycle. This visual helps students, and teachers, keep track of where they are in their inquiry. The labels for these phases can be changed or combined, but the major ideas include:

The Challenge – statement poses a complex goal to the students. As mentioned earlier, the challenge is designed to target the integration of fundamental concepts that students must understand in order to solve the problem. This Challenge statement can provide background knowledge to illustrate how it relates to the domain and an explicit description of what students should know and be able to do at the end of the module. For example, evaluate the design of two medical instruments to do the same function but using two different techniques.

Generate ideas (or **initial thoughts**) – provides students with the opportunity to explore what they currently know about the challenge. This includes their naïve concepts, or models, of the domain. This can be an excellent opportunity for students to record their ideas using methods like on line journals. This provides a baseline or pre assessment of what they know about the challenge and how they approach it. The teacher and students can use these journal entries to illustrate the growth in their thinking.

Multiple Perspectives – are statements by "experts" explaining what they see in the challenge. Their comments provide insights into various dimensions of the challenge, but do not provide a direct solution to the challenge. Students can compare their initial thoughts with the experts, which will focus their attention on specific goals for the learning activities detailed in Research and Revise phase.

Research and Revise – contains a series of learning activities designed to help students focus on the important dimensions of the challenge (these include the ones presented in multiple perspectives). These *learning activities* are designed to help students make a link to the original "Challenge". Therefore, these activities make a statement about the goal of the activity and point to a resource, or collection of resources, to help students achieve that goal. The resources can include simulations, homework problems, lectures, labs, readings, urls etc.

Test your Mettle – provides students with the opportunity to apply what they know and evaluate what they need to study more. This assessment method helps students' reflection on how well they've learned the content of Research and Revise and to evaluate if they are ready to Go Public with what they know. These can be homework questions, on line quizzes or an essay that synthesizes ideas they have studied in Research and Revise.

Go Public – is the final assessment of what students know at the end of the module. This assessment could be a presentation of the content, a quiz or test, an essay or homework assignment, etc.

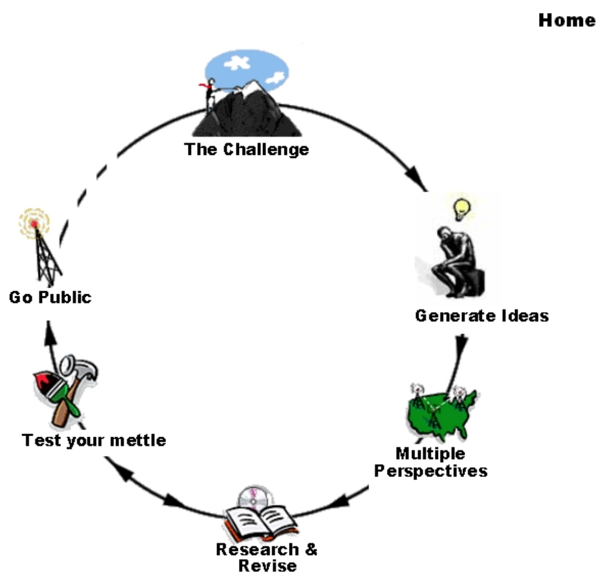

Figure 1- STAR.Legacy Software Reflection for Action and Reflection

<u>3.2 General Principles of Instruction embedded in Legacy</u>. The Legacy cycle and the use of challenges set up many opportunities for addressing the four major foci of the HPL Framework. Realizing these opportunities for effective instruction requires creative thinking around the knowledge to be learned (learning objectives) and the evolving understanding of the students. Legacy's Learning Cycle embodies a model of inquiry designed to help students develop their understanding of a domain. In general, the goals of the cycle follow several general principles for creating an effective learning environment including (but not limited to):

- **Contextualize the knowledge**. Challenges provide a goal state for the students to understand how knowledge is to be applied. Even if they don't possess the skills to solve the problem, the challenge provides an orientation for the content to be learned. Often we want to save larger challenges until students have learned the basics first so they have the tools to solve it. The challenge based approach merely gives them the goals of the knowledge right up front. *Awareness of this goal is one of the features that help students assess their progress toward understanding.* Further, an important problem solving skill is identifying and defining a problem. Starting with a complex challenge provides students with the opportunity to decompose a problem into independent sub problems.
- **Students need to generate and demonstrate what they know (formative assessments)**. Students need multiple opportunities to express what they know and can do relative to the learning objectives established for the course. Therefore, activities like generating ideas, then comparing them with those of experts is one method for them to articulate what they know and test it by listening to experts. This is an informal formative assessment (i.e. informal because it's not graded). Another option is to use a testing system to diagnose were they are before going into a series of Research and Revise activities. The result of this diagnosis can be used to prioritize the sequence and time spent on the learning activities in Research and Revise.
- **Illustrate knowledge in multiple contexts**. A single challenge will help students "conditionalize" the knowledge to be learned; that is, help see the conditions in which the knowledge can be used. However, even students who perform well on one challenge may not understand how to apply it to new situations. Therefore, students need to explore several similar challenges to understand the general conditions under which the knowledge can be used. Therefore, grouping challenges together will help students compare and contrast the solutions of challenges. This comparison process will help them notice the subtle differences between these challenges.

- **Making students aware of the learning process**. The Challenge Based approach is a new form of instruction that requires establishing a new set of norms for the students. They will be challenged in unconventional ways and they need to be aware that anxiety about not understanding something is a part of the learning process. It needs to be made clear that many of the larger challenges will take time to solve.
- **Use what they generate**. Students are frustrated when what they create is not used for anything. They feel as though the process is only busy work. Therefore, anything you ask students to produce (e.g. generate ideas, test your mettle, or part of Resources), should be incorporated into future activities or for feedback to help improve their performance. For example, if students generate ideas prior to class and post them on the web or in the email, then review these materials as part of the class period. A simple synthesis of the main ideas students generate may be just what is needed to establish a conversation or dialogue with the students.

There are many techniques for designing learning activities for each phase of Legacy's learning cycle. Maintaining these principles above will help to design an effective learning environment for learning and student satisfaction. The activities are a function of the domain knowledge, and available resources. Also, as mentioned earlier, the pedagogical challenge is deciding what to do prior to class, in class and after class. The Legacy cycle is not defined by temporal constraints; therefore, multiple methods can be used to organize in class versus out of class activities.

The legacy cycle can take on many different forms and levels of formality. Some challenges will require a sustained level of inquiry requiring days to complete. These more intense investigations may end in formal assessment of students ability to synthesize and communicate the concepts research as part of the project. Alternatively, modules may be simple challenges designed to orient students to the major issues of a design. These could end with an informal "Go Public" activity that ask students to make a prediction about the outcome of an experiment, or to draw their own representation for how to manage the complexity of a complex systems. For example, in systems physiology an initial challenge to the cardiovascular system could consist of a mini challenge to describe the causal chain of events of an asthma attack. The product of this challenge would be a simple block diagram that students create to describe the sequence of events. They would revise this representation of the cardiovascular system as part of their exploration of other dynamic effects of the cardiovascular system. This decision is a function of where students are in their understanding of a domain the relationship of the challenge to other challenges. Lets take a look at one example of how Legacy can organize learning activities.

3.3 EXAMPLES of Legacy Cycle: Introduction to Electronics Lab

Example 1 – Preparing for a Lab (see http://extend.ltc.vanderbilt.edu/vanth/ for EE213 example)

This first example illustrates one method for organizing the phases of the Legacy cycle for a lab class. The Legacy cycle prepares students for their lab experiment by posing a challenge that utilizes knowledge they develop during the in lab experience. The first four phases (the challenges, generate ideas, perspectives and research and revise) are all done prior to the lab activity. If they have studied well for the lab, then they are ready to Test Their Mettle during the lab experiment. After completing the lab experiment, the students should be well prepared to "Go public" by writing a lab report that addresses the solution to the original challenge in terms of a formal report.

This example relates to an electrical engineering laboratory taken by all bioengineers at Vanderbilt University. One of the major goals for the first lab is to explore the fundamental properties of frequency and how to control it using resister-capacitor (RC) and resister-inductor (RI) filters as low- high- pass filters. The learning objectives for this lab could include having students be able to –

- Explain how a low- high- pass filter works
- Evaluate a filters' performance, and how to change its characteristics
- Calculate the "order" of a filter and change its characteristics to achieve a specific order
- Explain the differences between various orders of the filter

The traditional lab manual (used for the past 20 years) provides a theoretical description of a filter in terms of its components and mathematical representation. Next, it provides a list of procedures designed to give students a data set they can use to represent the performance of the filter (magnitude and phase plots). The Legacy approach is designed to provide a context for how these filters could be used and to help build students' intuitions about the properties of filters as they relate to frequency. Therefore, the

Legacy cycle begins with a challenge and a set of activities that students perform prior to entering the lab setting. Here is one sequence of activities designed to engage students in the process of learning how to design and evaluate a filter's performance. In this module only the lab experiment in Test Your Mettle is done with the instructor's supervision. All the other activities are done by the students either pre or post lab time.

The challenge places the students in the role of design engineer for an audio component manufacturer who needs a set of filters to meet specifications for a set of speakers. The challenge statement could include a little background information, for example :

The Challenge – [The challenge begins with a brief introduction of the focus for the challenge, then sets up a scenario]

Introduction: The goal of this lab is to explore how filters work, how to measure their performance and how to design for multiple applications. We will be exploring the characteristics of these filters in a common filtering method used in audio systems like the ones in the stereo systems you use in your dorm, in your car and television. Start by reading about this interesting scenario and then try the challenge.

Scenario: You are a member of a joint development team made up of members located at Sony Corporation's Offices in Europe, Japan and USA. The team has been assigned to design the speakers for a new hi-fi system under development. The members are also involved in other projects at the same time so your means of dialogue will be over the Internet using the Prometheus conferencing system recently installed by Sony Corporation. The normal practice in designing speaker systems at Sony Corporation is to experiment with different components and establish the frequency bands to be handled by each speaker in the system. Inventory records show that only woofer and tweeter shipments have been received. The shipment of mid-range speakers is expected to arrive next week. The team has decided not to waste time waiting for the shipment of the mid-range speakers to arrive but initiate work with the woofer and tweeter. The specifications show that the woofer can handle frequencies from 0Hz to 1KHz. The tweeter can handle frequencies from 2KHz and above. You have an assortment of resistors, capacitors and inductors and a breadboard to experiment with.

The team's task is to develop two prototype filter circuits, one for the woofer and the other for the tweeter and each using both capacitor/resistor and inductor/resistor combinations. This will ensure that if components in one combination run out, work can still proceed with the other combination.

In, the next phase**, Generating Ideas**, students are asked to use an online discussion area where students share their initial thoughts about what they need to consider in the design of the filter. In general, Generating Ideas is designed to help students reflect on what they currently know about a topic before they explore it in more detailed. Another technique used for this section is to have them take a test to see what they know. Therefore, students access an on line assessment system where they can test their knowledge about the principles of frequency and about the particulars of the lab procedures (e.g. procedures for the equipment used, normal procedures for the lab, and other basic measurements).

Then, in **Multiple Perspectives**, experts could provide insights into ideas about how to represent the performance of a filter, or display the range of application of "filters" beyond audio application into fields like medical imaging and signal processing of medical instruments. Students can compare the initial ideas they shared in their discussion area with the ideas presented by the experts. This process of comparing and contrasting should help them understand the range of the problem space for this challenge and what more they need to investigate.

Research and Revise is designed to help students focus on issues they raised in "Generate Ideas" and by the experts in multiple perspectives. Based on our initial learning objectives, a set of pre lab activities could be designed to link various granules together. For example, a set of granules designed to demonstrate various properties of frequency and filters. The students could be asked to explore each of these activities prior to the final experimental activity -- the lab experiment. These activities might include –

Activity 1 – Exploring Frequency (several video demonstrations of an oscilloscope trace to illustrate ideas such as amplitude, input and output signals and filter performance.)

Activity 2 – Description of filters

Activity 3 – Mini challenge – Try to identify and explain what changes over time as the input frequency to a low pass filter is increased.

Activity 4 – Building Tools to use in the lab (given a sample RC Filter and a set of frequency versus amplitude data, predict the cut off frequency both mathematically and graphically.)

The Research and Revise activities prepared them to be able to "Test Your Mettle". In this phase the activity is the actual lab experiment detailed in the laboratory manual. Once they are done with the lab they can further test their mettle by returning to the online assessment system evaluate their change their ability to answer the questions in the assessment system.

The final phase of the process allows students to **Go Public** with what they know. In this case, the final lab report is their product. To help students improve their performance, the instructor can provide guidelines for creating a good report. In addition the instructor could provide sample reports that illustrate the characteristics of a good report. This way, students must identify what makes this a good report and emulate the processes in their own work. Students may be creating their own *legacy* by providing a sterling report for future generation of Lab recipients.

Summary of Example 1

This lab example illustrates how a single challenge can be used to set up a series of activities to explore some of the abstract principles of filters. In designing the activity, we make the assumption that not everyone is aware of what a filter is or how to monitor its performance. Therefore, the pre-lab activities are designed to give the students a little background into the world of filters and how to apply them in various situations. In addition, the pre lab activities can help the instructor establish a common ground for discussion. If the instructor begins under the assumptions that all the students have looked at the material, then the instructor can confidently reference these materials in a discussion with the students, either individually or in small groups. Finally, this module has some overlap with other labs, but in general it targets a specific set of learning objectives independent of other labs. Therefore, all the labs in this course are independent modules. This is not always the case for instruction.

4. Legacy, Modules and Mosaics

Several common questions about Legacy include - how long should a Legacy cycle take to complete? Should the challenges be so complex that they require weeks of inquiry to complete? Another often asked question is could there be a Legacy within a Legacy? These questions get at the heart of how to divide up challenges in a way that supports students' evolution of understanding for a challenge. The important thing to remember is that Legacy is a framework for systematically thinking about how to organize instruction to enhance students' learning with understanding. Instruction for a major area of a course can begin with a complex challenge that could take a long time to explore. Identifying a solution to a complex problem (e.g. design tasks) will require reducing the complexity to smaller sub problems to solve. Therefore, instruction around a major unit of the course can be organized around a single challenge, but many smaller challenges can be used to explore smaller units of study. We have used the term "Mosaic of Modules" to describe the clustering of several smaller challenges around a larger challenge or around a unifying theme that categorizes smaller challenges. The larger challenge of a Mosaic could take weeks to complete. The smaller, more focused challenges could be as short, or shorter than a class period or an evening's study by a student. The following describes several ways of thinking about how to organize modules into Mosaics.

4.1 Mosaics around Big Ideas

Modules in a course will develop interdependence with each other in several ways. Modules can be clustered together to help students explore a major concept area from several different dimensions. The goal is to help students develop an understanding of a concept area based on the underlying principles of the problem rather than the superficial features of the problem. As Chi et al., (1981) illustrate, experts classify classic physics problems based on universal laws, or first principles, like Newton's Laws of motion. Novices tend to classify problems by the superficial features of the problem like, a pulley problem or an incline plane. A series of modules can be designed and clustered to help students notice important features about a problem that will help them classify it based on first principles. This classification method is what helps them determine the proper representation for the problem and ultimately the right equations to use to solve the problem.

For example, a Mosaic of modules for biomechanics could explore concepts related to how the human body simultaneously achieves feats of strength and large range of motion. The focus of the investigation will require the use of force balance equations to the various classes of lever systems to illustrate the principles of mechanical advantage. The central challenge could revolve around explaining how athletes can throw a football or baseball overhand versus an alternative style to propel a heavy ball like a shot put. The sequence of challenges would be designed to help students make the connection between classic physics systems (eg. Lever and pulley systems) toward the biological equivalent systems found in the body (eg. Bone/joint/muscle/tendon systems which combine lever and pulley systems). The first few challenges could review the force analysis of simple systems that students learned in the physics prerequisite course. The initial challenge would ask students to compare the force analysis of various joint and muscle characteristics such as the images in figure 3. In the Legacy phase "Generate Ideas" students could articulate what they need to know to determine the forces on the body and identify the critical features to notice in each figure (e.g. the ⊥ distance between the pivot point and the insertion point of the muscle). Each would represent a different class of lever systems. As part of the Research and Revise activities the professor could review the force equilibrium analysis of the three types of lever systems, in figure 3, then ask students to classify the various muscle/bone systems as a lever system. The goal is to help students recognize these types of systems in the body and fluently categorize them into their class of level system and the relative mechanical advantage quantity (ie. Mechanical Advantage > = < 1).

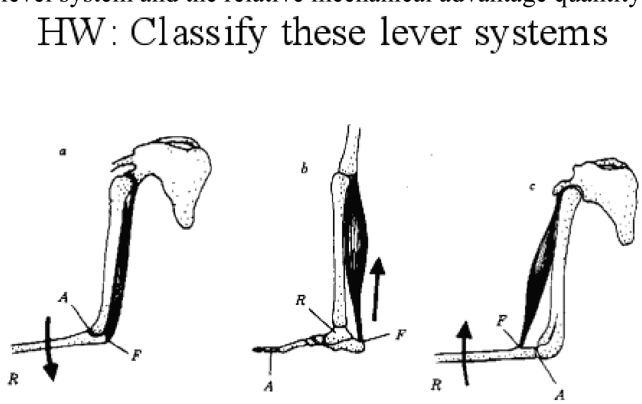

Figure 3. Identify the types of lever systems

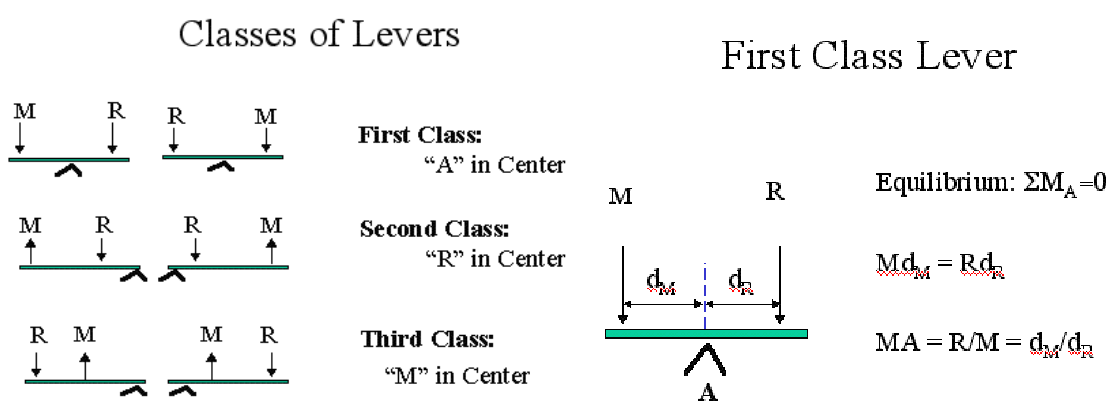

Figure 4. (Images from Roselli's Lecture notes for Session 10 Spring 2000).

Together the professor and students can analyze the force equations within the three classes (e.g. Figure 3) to determine the mechanical advantage of each lever. Once students understand mechanical advantage they can begin to understand what effects this has on muscle/bone/joint design. This exploration of lever types will illustrate the importance of insertion points of the muscle into the bone and what it means to function and size of the muscle. Further, this can lead to exploration of the various possible alignment patterns of muscle fibers to combine strength and range of motion. Therefore, an additional challenge could be to solve several "what if" problems around changes in the insertion points in Figure 2 and explain what this means to the range of motion. This first challenge is designed to help students develop a qualitative sense for some of the basic mechanical systems in the body. Now they should be better prepared to recognize these systems in other contexts.

The second challenge has a range of possibilities to help students continue to explore mechanical advantage and muscle systems then introduce joints that have force characteristics similar to pulley systems. The challenge could be to define the applied forces of the shot putter propelling a 16-pound ball to maximize the distance it can be thrown. The analysis would consist of exploring the forces exerted at the several different positions, define the role each muscle plays and how much they contribute to moving the ball. Alternatively, the second challenge could focus on a figure skater pushing off of a skate to induce motion. Or the challenge could focus on defining how the forces in each leg contribute to a skater. An additional challenge might analyze forces when the skater lands on one skate after a leap. Or, the challenge could simply be the forces necessary to stand up from a sitting position with two legs versus one leg as is the case in an amputee or stroke patient.

The general principle for the mosaic of module design is that the progression of modules increases in difficulty by introducing more factors into the analysis, such as starting with simple levers in two dimensions and moving into rotator joints in three dimensions. Therefore, the next challenge would return to the original Mosaic challenge of an athlete demonstrating strength and range of motion, like throwing a ball overhand. The students could perform a static force analysis at different stages of a throwing motion. Of course this ignores the dynamic forces by only considering the weight of the ball in each position and not the momentum forces. However, this sets up the topic for future Mosaic of Models targeting Dynamic force analysis. This final challenge for statics analysis could be the starting point for dynamics.

4.2 Mosaics around Complex Challenges

The example above links modules together based on their relationship to fundamental physics properties as they relate to the human anatomy. Another way to group modules into Mosaics is around a complex challenge, such as a design task. Complex challenges require decomposing the problem into smaller more independent sub-problems. Then each sub problem can be explored in more depth, within the context of the larger challenge (which is one of the general principles mentioned in the description of the Legacy Cycle). The process of exploring these smaller sub problems could be organized around a smaller Mosaic of Modules as described in the previous example. For example, an interesting challenge in biotechnology is designing a bioreactor for the production of cells. The design challenge requires balancing several constraints simultaneously in a way that maximizes cell growth. The process requires choosing the right reactor type to achieve the desired cell growth rate. Each reactor type has a different method of providing oxygen to the cells. Some reactor types use mechanical methods that increase the amount of available oxygen to the cells, but these methods also increase the risk of cell damage. Therefore, this series of modules needs to help students be able to identify an optimal design for a reactor type to achieve a certain cell rate. The fundamental learning objectives of this challenge might include

3 Identifying the critical factors that influence the design of a reactor type.
4 Describe the metabolic rate of cells and how it relates to a reactor design
5 Calculate the O2 rate of delivery for each reactor type and the O2 consumption rate of the cells.
6 Determine the amount of mechanical damage for various configurations of different reactor types.

The first challenge for this design activity focuses on describing a qualitative model of a reactor's design. This will require students to revisit their studies in mass transport and provide an opportunity to learn about cell anatomy and other cell characteristics. Most undergraduates have little access to bioreactors; therefore, the initial challenge is a small design challenge around a simple bioreactor to grow a small quantity of cells. Students begin their inquiry by generating their initial thoughts about the major factors influencing the design of the reactor. Experts from research and industry provide their perspectives on several reactor types. The *Research and Revise* activities provide students with the opportunity to research each of the reactor types in more detail. The major objective is to help students develop a ***qualitative*** sense for how cells grow and how the reactor works. For example, students can view a reactor from multiple dimensions using a standard virtual QuickTime movie format. With this tool they can rotate the object in space and look it from various sides and angles. An interactive simulation allows students to control various factors of a reactor, such as volume and depth of fluid, to gain a sense for how these factors influence the cell production. Also, a short animation can provide students with a mental model for how cells grow and how they receive oxygen in the different reactor types. Once students have reviewed these materials, they take a short online quiz to help them evaluate how well they understood the material. Once they pass this quiz in "Test your Mettle", then they can place a vote for the best design in the "Go Public" portion of Legacy. As part of Going Public, they could write a short justification for their answer. This will be used to compare with the quantitative analysis they will perform in the second challenge.

So when do the students do these activities? This could easily be a teacher-guided activity where the students have access to a computer during class to use the interactive portion of Research and Revise activities (eg simulations, animations). However, for an undergraduate course, this could be just the kind of activity the students need to engage in prior to coming to class. The degree of difficulty for this first challenge is such that students could think through the major issues and explore the resources. Therefore, this module would take students an hour or two to go through. Pre class activities like this one will prime students for the next challenge, which could be guided by the instructor during class.

The second challenge in this bioreactor design Mosaic takes a more quantitative approach to the design. This challenge changes the design constraint to require a higher production rate of the desired product. In "Generate Ideas" students can discuss whether their previous design will work or what they need to change to make it work. The experts in the "Multiple Perspectives" provide new insights into how to size a bioreactor to meet specific production rates and some of the pros and cons of the design. Now, as part of the Research and Revise section an Instructor provides a lecture to explore the types of calculations necessary to determine values such as oxygen delivery, oxygen consumption and minimization of cell damage in the process. This may take several lectures, but between each lecture, students could be assigned homework problems to apply the ideas demonstrated by the professor in class. The final "Go Public" would be for students to justify their original votes for a particular bioreactor design for the initial challenge, or refine their vote and substantiate it quantitatively.

A possible final challenge could focus on a challenge similar to the second challenge, but target the analysis for a different bioreactor type. For example, the optimal solution in the second challenge could be to use a stir type bioreactor to achieve the desired cell production rate. The third challenge could focus on a hollow fiber design model. The objective of the challenges would be to explore the pros and cons of each design. One of the important goals of this third challenge is to provide an opportunity to apply fundamental principles of the domain to a new context. This use of multiple contexts should help students generalize the application of the knowledge they learned during the second challenge.

4.3 Summary for Mosaic of Modules

Mosaics of Modules are a collection of modules, which comprise challenges and learning activities, designed to help students explore the application of domain knowledge to several different situations. The challenges can be linked by the relationship to fundamental principles of a domain, such as applying Newton's First Law or sub problems associated with a larger challenge. The goal of the mosaic is to help students compare and contrast various situations, which helps them notice the subtle differences in each situation. Another method for linking modules into mosaics is around a major challenge that requires solving multiple sub problems. Each module in the mosaic could target the concepts associated with a specific challenge. The challenges could be sequenced based on their level of difficulty (or amount of new knowledge to be learned). Alternatively, the initial challenge could be designed to help students orient themselves to the subtleties of a challenge. In addition, the activities should be designed to help students obtain a *qualitative* sense, or mental model, for how the system works. It is this type of *qualitative* model that helps students make inferences about a new context. The activities could be performed outside of class to better prepare students for interaction with the professor during class. The in class activities could revolve around developing the *quantitative* representations necessary for solving the various challenges and for students to ask and answer questions.

The design decisions for creating each modules and mosaics requires thinking about what students need to know, what knowledge they already possess, identifying what needs to be taught in class with the aid of the instructor and what the students can do on their own. This report focuses primarily on several dimensions for establishing an effective learning environment. The initial activities target the identification and prioritization of the knowledge the students should be able to apply. The discussion of the HPL framework focused on methods to organize learning activities to help students build their understanding of the domain knowledge and to assess their progress toward better understanding. However, more can be said about how to establish a climate for learning. Future reports will address the opportunities for establishing collaboration between students and methods for more objective assessments of students' progress.

5 Conclusion

This report explored two major dimensions for defining the scope and structure for a course. First, the report describes a method for identifying the critical content to cover in a course and defining the learning objectives that describe how students should be able to demonstrate their understanding of this content. The taxonomy of the domain defines a nearly exhaustive description of a specific domain. The first step for defining a course is to identify what sub-components of this taxonomy will be covered in the course. The second step is defining what students should be able to do with this content by the end of the course. Therefore, *learning objects* for a course describe how a student should demonstrate their understanding of the content in the course, such as, *calculate* the static force on a knee joint for a person walking up a stair. Or, explain the process for extracting specific proteins from a DNA sequence. The definition of these learning objectives can help define the kinds of assessment activities that can be used during the course. The second objective of this report describes a method for embedding these learning objectives into challenges to form *modules* of instruction. The modules are self contained units designed to help students focus on the principles and concepts related to a challenge. The *learning activities* help students differentiate the subtle difference between how the fundamental principles of the domain relate to various applications. These learning activities can put a context around *granules* like simulations, homework problems, animations etc. to help students explore specific principles in-depth that apply to the challenge presented at the beginning of the module. The principles of the HPL framework can be used to help make decisions for how to define these learning activities. Also, the STAR.Legacy template is one method for illustrating how to sequence these learning activities using this HPL Framework. This report provides several examples for how modules can be developed using the Legacy framework to create modules related to bioengineering applications. (The Legacy framework provides a structure to help designers remember these critical components. Within VaNTH we will need to explore various representation for how this will work for the domain of engineering.) Finally, we discussed how to link modules together into *Mosaics* as a method to help students make links to how the fundamental principles they learn in smaller challenge related to larger concepts and more complex challenges. At the end of a course students should have a representation of the domain that allows them to make connection between the fundamental principles of the domain, described by the taxonomy, and how these apply to various problems within the domain.

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