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Managing Project Scope for Successful Engineering Capstone Projects*

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Cultivating the relationship between industry representatives and capstone instructors is an important and often overlooked first step in running a successful capstone program with externally-sponsored projects. In this article, a problem scoping philosophy and supporting methodology is presented for generating shared understanding about the project starting point and the intended project deliverables. The article traces steps from initial project dialogue with the client, to current technology assessment, to assessment of available resources, to management of uncertainty within the arc of the project, and finally to drafting of a project scoping document that is suitable for inclusion in a class-wide portfolio of capstone project options. The methodology is derived from the NASA rubric for Technology Readiness Levels (TRLs). The resulting problem scoping template has been used successfully by the authors to secure over $2M in funding for capstone projects over the last fifteen years. Statistics about the success of project descriptions with different TRL levels and resource requirements are presented. The approach outlined here is especially well-suited to projects with client-approved deliverables. It can be used in conjunction with a negotiation for early agreement mindset to settle on an accessible problem scope which faculty and students can use to sort out alternative project options as well as provide a robust starting point for each project team.

Keywords: capstone project scoping; technology readiness levels; resource assessment

1. Introduction

Once demonstrated completion of senior capstone projects, with some level of rigor, becomes a capstone class requirement, a challenging requirement that emerges is that an entire slate of projects must be successful, with a high level of statistical certainty, by a diverse group of students working on different design teams [1]. This is not a trivial challenge, as the state of the project at completion is often used to validate the project budget or to influence the level of industry commitment to follow-on projects. The more money a corporate or outside agent invests in a given project, the greater their exposure and responsibility [2]. In order to fulfill this duty successfully, a harder 'second look' is required on what students will actually do. All instructors involved with such programs know intrinsically the difference and liability for end results between being asked by a sponsor, for example, to 'reduce greenhouse gases' or 'make our facility more environmentally friendly' in contrast to 're-engineer the ducting system using state-of-the-art sensor technology to reduce pollution emitted by 20%'. The first is likely to be paid for by foundation funds associated with the corporate sponsor, and to be disbursed regardless of result. The second is likely pulled, at least in part, by the sponsor from operating funds, with direct accountability to upper management. This paper is focused on capstone project recruiting and scoping for the second type of project where the deliverable must be client-accepted.

The need for a client-accepted deliverable requires a responsibility matrix that is different from a traditional course. Since capstone classes typically are filled with seniors, often ready to graduate, there is no 'second chance' associated with failing or dropping the class. Instructors, through direct relationships or through development staff inside their own organizations, have commitments as well, and there are relationships that could be sacrificed if deliverable goals are not met. Furthermore, when a given senior does not graduate, there are often institutional repercussions. The idea that performance rests entirely on the students' shoulders, to be assessed with grades, must shift the locus of responsibility in the student/

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sponsor/instructor system [3]. As such, the proper role of the capstone instructor is to facilitate high performance of the student group whenever possible, instead of falling back on a more passive, transactional, or even authoritarian form of project management [4].

A key part of project selection and scoping is the relative difficulty of the project. Even with a supportive sponsor, projects should include measurable learning outcomes laid out as part of departmental ABET objectives [5]. Projects cannot be trivial, and must possess realistic constraints, as well as potential intersections with codes and standards [6]. How to manage all these topics makes project acquisition non-trivial, and turns out to be extremely challenging for first-time faculty [7] .The intent of this paper is to provide a roadmap for project scoping which can be readily used by instructors at any experience level who find themselves responsible for capstone project procurement from third parties.

In an attempt to provide scaffolding for the capstone project scoping process, we have assembled the following questions to explore how a high quality, validated scoping statement could be obtained. The questions are:

- What issues are involved in scoping a capstone design project?
- Can we apply a rubric for scoping capstone projects derived from generally accepted government/industry techniques such as the NASA Technology Readiness Levels (TRLs)?
- What constitutes realistic evidence of completion for each level?
- How should one consider resource availability for completing projects?
- How should one account for uncertainty in project negotiations and how does one establish an acceptable fallback position in case initial deliverables are unable to be met?
- How do we write a scoping statement that captures the essence of a project, the criteria for successful completion, and project features that can also help in assigning students to different teams?

2. Background

Project scoping is the process of laying out the rough outlines and expectations of a design process/project—a well-founded expectation that creates a platform for students to move forward. This varies from specification writing that involves generating more complex and in-depth customer needs and metrics. Scoping is completed at the outset of a project, and presages specification. In the authors' classes, students are required to complete the specification, based on Quality Function Deployment techniques that are part of a Six Sigma repertoire of skills/documentation [8]. Given the temporal and curricular constraints surrounding a capstone class, the responsibility for initial scoping, as well as writing the scope document, rests on the class instructor.

The biggest challenge, however, is how to handle uncertainty in the final output. There can be a world of difference between designing a cart, using an ensemble of off-the-shelf components, each subject to appropriate engineering analysis for strength, weight and other performance measures, and creating a testbed for a new technology that may be incorporated into a new line of products. Both types of projects can be successfully completed by students. However, they will have profoundly different requirements, and the achieved outcomes will look very different.

Most aspects of engineering education are centered on acquisition and demonstration of knowledge proficiency. Well-recognized curricula for subjects such as thermodynamics, statics, or circuit analysis are established in the canon of knowledge, and students are typically taught these subjects, with varying levels of social interaction, in a typical classroom, with proficiency in given learning outcomes demonstrated through well-characterized assignments and objective testing [9]. The knowledge students are expected to acquire by the end of the term is known a priori by the instructor and others in the field of study.

Knowledge after a design experience, however, is not nearly as well structured [10]. According to typical learning outcomes and ABET criteria, students are expected to demonstrate certain skills, such as the ability to follow a design process, communicate effectively with teams, and so on [11]. But in the course of executing a given design project, it is not realistic to expect that students will know all the knowledge they need to complete a given project at the outset [12]. Students may be well-couched in their discipline, but that is no guarantee that learning of new information will not be required in the course of project execution. In fact, students may be required to create knowledge, or one of the deliverables may in fact be creation of knowledge that was hitherto unknown. On top of this, neither the instructor nor the sponsor may know all the necessary information.

What this means is that all three primary constituencies—the students, the instructor, as well as the client—will be embarking a metacognitive journey with an uncertain destination [13]. There will be the 'known knowns', the 'known unknowns', as well as the 'unknown unknowns' all embedded in the project. When students have projects where larger unknowns are present, accurately scheduling and estimating time requirements becomes a serious challenge.

Typical scheduling tools taught to engineering students, such as Gantt charts, or CPM, are those that are commonly used in industry [14]. However, within a capstone course context, students often trivialize their use, replacing these with more familiar social media platforms [15]. What professor has not seen the essential linear bar graph of 'Research—Design—Manufacturing' included with no detail? Or even if tasks are broken down in a more elegant fashion using techniques such as the Critical Path Method, students, even if they are aware of what path holds the largest body of work, will very often burn the 'slack' on the other branches of the schedule. Where once there was only one critical path for the project, with the tendency of students (and often professors!) to put things off, now there are multiple paths where unknowns of different varieties can pop up, all dramatically increasing the odds of project incompletion.

3. Methodology

3.1 Technology readiness levels

This work began with an exploration of government/industry methods that could be adapted to produce a method for capstone project scoping. John C. Mankins provided such a tool in his extensive review of Technology Readiness Levels (TRLs) associated with NASA projects from 1970–2009 [16]. In Mankin's words, TRLs are intended "as a discipline-independent, programmatic figure of merit (FOM) to allow more effective assessment of, and communication regarding the maturity of new technologies." TRLs thereby reduce uncertainty in the project dimensions of performance, schedule, and budget. Use of TRLs continue to increase with technology failures becoming increasingly unacceptable and they are now used as a technology assessment metric in nearly every development branch of the federal government, including NASA, the Department of Defense, the Department of Energy, and the National Institute of Health [17–20]. The TRLs are, from bottom to top:

- TRL 1—Basic principles observed and reported.
- TRL 2—Technology concept or application formulated.
- TRL 3—Analytical and experimental critical function and/or characteristic proof-of-concept
- TRL 4—Component and/or breadboard validation in a laboratory environment
- TRL 5—Component and/or breadboard validation in relevant environment
- TRL 6—System/sub-system model or prototype demonstration in a relevant environment
- TRL 7—System prototype demonstration in the expected operational environment
- TRL 8—Actual system completed and "qualified" through test and demonstration
- TRL 9—Actual system "flight proven" through successful mission operations
- TRL 10—Legacy systems with 'frozen' designs

TRLs are further paired into common project cycle transitions. These pairings are then instructive for assessing suitability as capstone engineering projects.

TRL 1–2: This consists of basic, hypothesis-driven research to understand the physics of the key phenomena and mechanisms underlying a problem. Although these may be appropriate projects for senior theses in science-based curriculums or graduate students, they are not appropriate for undergraduate engineering projects. The governing physical mechanisms are not understood to allow parametric-based proof-of-concept, let alone product design. These types of projects are characterized by design spaces full of known unknowns, and as yet to be discovered unknown unknowns. Because of this, indeterminate timescales dominate, and these are not as useful on a closed schedule with fixed resources.

TRL 3–4: These are generally proof-of-concept experiments that demonstrate how a theoretical model in simplified solution space can explain basic experimental measurements. These can be appropriate as capstone projects and ideal for students wanting to continue on to graduate school or research careers. Useful approaches at this TRL can be to develop test apparatus for a fixed number of concepts, and report out on whether there is critical success, or critical flaws in a given concept.

TRL 5–6: These are applied technology projects that begin with specific customer requirements and an end-use environment. Multiple TRL 3–4 concepts are available as potentially viable solutions and a primary challenge is selecting the most feasible ones for a task, or identifying the most viable tasks for a new technology. These are prime capstone projects. Expectations for completion for a capstone project will involve developing, and likely constructing, some element of multiple solution design, with benchmarking of key metrics being limited to off-the-shelf measurement equipment.

TRL 7–8: This involves actual testing of the solution and revision in the appropriate environment. These are appropriate as capstone projects if sufficiently robust communication and testing is afforded to the students. Projects in this space may require development of experimental equipment and test plans to validate requirements—something that should be included in the scope. In some instances, multi-phase projects extending over two capstone project cycles may be advisable for achieving this level of technology readiness.

TRL 9–10: These are legacy, ready-to-install technologies that can be artfully modified for slightly different applications. Such projects are suitable for experienced engineers in industry, not capstone design students. What typically happens in these scenarios is that students end up losing agency in teamwork, as they typically do not have the experience or insight to make progress without direct supervision from the client.

Once the starting TRL is determined, the desired TRL at project closure must be determined with the help of the sponsor. Again, the ending TRL should ideally fall between TRL 4-8 and should generate doubts about successful completion of the final TRL is more than two TRL levels away from the starting condition, as available time and budget resources will likely not allow for more ambitious advancement. However, the viability of advancing the TRL from the current state to the client desired level is also contingent on an assessment of the available resources.

3.2 Resource assessment

Resource assessment is critical when undertaking engineering project [14]. Often, students can complete complex assemblies of parts, but only if substructures such as larger bearing assemblies or guides, for example, can be purchased off the shelf. In general, though, these resources can be lumped into the following core dimensions: space, time, energy, information, and funding. A working definition for each dimension follows.

Space: Can the project be constructed in the space available? Some projects that are assembled on benchtops do not pose this problem. However, working with large aerospace concerns, or steel mills, will often require a completion commitment at some sort of scale. One of the authors' projects involved a load cell test of a thrust reverser removal device for an engine on a Boeing 787. Needless to say, this frame tested the limits of the university's facilities.

Time: Students only have so much time in a semester, or over the course of a year, to work on their capstone projects. This varies based on a school's curriculum and student capabilities. The number of components to be individually designed and produced, versus purchased, increases time required for the project. Additionally, special components that may be required for project can have lead times that take weeks, and this delivery time must be estimated a priori by both the sponsor and the instructor, if physical completion is a requirement.

Energetics: Project energetics have many angles for estimation, from monetary commitment to actual power requirements, or volatility in final solutions. One of the authors used to have temperature limitations on any project to be given (e.g. no project requirement of temperatures greater than 1100 F to be handled on-site, for example.) Projects requiring special safety training can be completed as capstone projects, but care is needed. One technique utilized in the lead author's clinic is a safety audit by the environmental health and safety division of the university. Including such individuals a priori can not only avoid potential catastrophe, but also improve design and enlarge the students' metacognitive reach.

Energy storage and power density are also good measures of suitability for capstone projects. One project for design of a long-range UAV required Li-Ion batteries that could potentially explode on impact. The project was a success, but required development of a safety protocol for disposal of damaged batteries. Another project involving creating a testbed for a generator for an aircraft Auxiliary Power Unit (APU), spun at 100K rpm and required 0.5'' steel shielding, as well as a safety audit before it was turned on for the first time. Students are capable of handling such technologies, but mindfulness and collaboration with safety professionals are key.

Information: Both the presence and lack of information (as well as its availability) are critical in scoping a capstone project. As outlined in our previous paper, working under an expert, with a carefully managed performance trajectory, can still be a creative experience. Faculty from the home department can compensate for gaps, and a comprehensive inventory of in-department research is often a good resource to take along when scoping projects.

Most important, though, is an appreciation of gaps in the information space, and the ability of students to fill them. Often, project sponsors will offer up projects that no one in their organization or industry has been able to solve. This is done in the spirit of ''let's see what these bright young minds come up with.'' As discussed above, projects like this can be completed successfully, but only if posed in the framework of TRL 3–4 paradigm investigation.

Sophistication of the project mentor must be factored into any decision making about capstone project suitability. A senior engineer at a sponsoring industry may have a strong intuitive feel about potential directions that they may want students to explore. The process of advice and consent will look far more different than dealing with an off-thestreet entrepreneur looking for low-cost engineering labor, that doesn't have a good grasp of the laws of thermodynamics. A tool for rating project mentor capabilities is helpful in setting up a plan for information management [13].

Funding: Monetary resources are critical for project success (materials acquisition, laboratory support, and travel) as well as flexibility (reserve funds that that can be exchanged for other resources like space, people—irregular help workers as well as graduate student mentors—, or information—paying a consultant.) It is also important when scoping projects to ensure that enough funds are available to justify the effort of procuring capstone projects that will ensure a robust design experience. A clinic-wide pricing policy, founded on historical data from past projects, is a good tool for communicating and justifying project costs to prospective sponsors

3.3 Managing project uncertainty

If there is one large stumbling block in the process of running a completion-oriented capstone class, it is managing uncertainty, or more precisely, the meta-cognitive load of information students need to process in order to successfully complete a design. This can be deconstructed into four different types of unknowns:

- *Type 1:* Information that the instructor and/or the project sponsor knows, but the students do not know (relatively easily discoverable)
- *Type 2:* Information unknown to the instructor and students, but known to the project sponsor (modestly discoverable)
- *Type 3:* Information unknown to the instructor, students and project sponsor, but likely to be known by the larger global community
- *Type 4:* Information unknown to the larger global community

For Type 1, this includes course content, such as a deeper understanding of the design process, tools for managing the schedule, as well as information acquired by the instructor from past projects. For the first author, a classic example might be appropriate use of linear bearings to prevent racking of moving carriages. His first project, over fifteen years ago, had an unsupported drive screw, which upon utilization, caused racking and binding of the movable stage. Now, as part of standard practice, he has students inspect moving carriages on lathes and CNC machines to understand prior art.

Type 2 unknowns fit neatly into capstone projects, and are easily constrained to the last half of the design process, following the Preliminary Design Review (PDR). The authors recommended that the project sponsor act solely as a customer, only focusing on transmission of requirements, for the first part of the project [13]. Once the PDR is passed, and a final design is settled upon, it is incumbent for the sponsor/client to lend student teams their specialized engineering knowledge in order to maximize value.

Type 3 unknowns typically arise in advanced applications, or purchased larger assemblies that are part of the solution set for capstone projects. An example might be that a gearbox may be a solution for powering a cart. Neither the instructor, students, nor sponsor may be experts in designing gearboxes, but there are many available vendor solutions. As such, after examination of environmental conditions and service life issues, specialized vendors will construct the gearbox, and students can prepare drawings for necessary mounting hardware.

Type 4 unknowns are the largest challenge in capstone projects, but with appropriate awareness, these can be managed. A key concept in doing so is awareness that testing will take time that must be incorporated into final deliverables, and that potential for failure exists. This can be managed with case-based hypothesis testing, where some assessment of different options is adapted by estimate of a given workload for a project. For example, students working on a project in the class involving cryogenic hydrogen, an area of interest to the space industry, but where relatively little is known about materials for seals, may design a chamber with three different types of testable seals. All of the seals may fail, but if this is integrated into the larger design, useful knowledge and customer benefit can still result, as the design space for the different seals will be considerably constrained after the testing is completed.

It is important to remember that unknowns exist at all TRLs and that uncertainty is integral to the capstone design experience. ABET specifically dictates that capstone design must contain open-ended projects, using realistic constraints, with applicable codes and standards [11]. However, tagging uncertainty is necessary in the scoping phase to calibrate sponsor expectations and to manage risk across the portfolio of class projects. When critical information is in the truly unknown category, completion needs to recognize that design space exploration is a valid part of the project deliverable.

3.4 Planning a project scoping visit

Generally, it is desirable for the project scoping process to work quickly in order to be completed during an initial client visit ahead of the start of the semester. For all TRLs where a relationship between the instructor and the sponsor has not been established, it is important for the instructor and sponsor to have a conference where some level of project deconstruction is done, and some specification of likely solutions are agree to, but not presented to the students. The first author has a '30 minute rule' about scoping—if the instructor and sponsor cannot either agree to uncertainty, or come up with a potential solution (not necessarily the solution the students will be expected to come up with) the problem is likely not a good capstone project.

A "binning" approach is recommended to sort the resource categories: RED—show stopper, YELLOW—have to think about it more, GREEN—not a problem. An example pertinent to the space resource is the problem of hoisting a heavy load. A 10-ton overhead crane is likely RED, not suitable given both the space required and the potential energy stored. A 2-ton electric hoist is likely YELLOW, potentially suitable if sufficient resources are provided to install the electric plug and fixture the crane. A load supporting frame with a one-time lift is likely GREEN, readily achievable with a portable rolling high-lift. Analogous binning of the time, energy, and information categories is possible. The authors recommend that three or more YELLOW flags associated with resources indicate too much difficulty. Just one or two YELLOW flags may be negotiable.

The meeting between the sponsor and instructor should not run over an hour (excluding such things as a plant tour). Remember that the purpose of a project recruiting visit is to define broad parameters, and do gross mapping of the design space. Students should be required to write the detailed specification after their own client visit/interview.

Finally, it is advisable for the instructor and the sponsor to agree on an 'overscope' of the problem. This places a stretch goal in front of the students so that they budget their time more appropriately, and builds potential slack into the system. Within the author's design clinics, an overscoping of 20% is commonly embedded in the project scoping documents that is given to students in their project selection and design team kick-off.

3.5 Drafting a scoping document

The final step in the project recruitment process, after a project scoping visit or conversation, is to organize information from the scoping interview into a problem scoping statement for a student audience. Considering the foregoing discussion, attributes of a good scoping statement are:

- Short and to-the-point (*no more than one typed page*.)
- Descriptive, accessible, and *attractive title* (especially to a student audience)
- Brief *profile of the sponsor* with whom the students will be working.
- Short explanation of the *context* surrounding the problem to be solved.
- List of anticipated *deliverables* and insight about what technology is involved.
- *Consistent with other scoping write-ups* so that students, if they are allowed to pick their project, they can make an informed choice discriminating among the different options.

One of the largest gaps in students' knowledge is the context of the project. Professors and industry partners often assume a greater familiarity with the work environment than most students. Grounding students in the product created, or service rendered by the company is an important first step. This is addressed in an early client interview/plant trip, immediately following project assignment.

It is also vital to clearly communicate the expected deliverable for the project. This is best expressed as either (a) a problem to be solved, which provides students with the greatest latitude for creative solution, or (b) a particular device/system that has some prior solution anchoring. The specified deliverable should be used to frame the specification that student teams will craft after their client interview.

4. Results

4.1 TRL rubric for capstone design

Effective and ongoing communication of project deliverables that are supported by evidence is essential for satisfactory project completion in the eyes of the sponsor. Examining TRL pairs introduced in the last section gives clear guidance on writing scoping documents that are useful for communicating progress to sponsors, as well as expectations for students. Below is a capstone-specific rubric that the authors have evolved and found useful for discussions with potential sponsors. This covers three common TRL groupings that apply to a product realization capstone course.

TRL 3–4—Primary expectation for these TRLs is project learning and awareness of constraints within a larger design space. Students typically have excellent divergent thinking skills, as their experience, being minimal, does not track to established design paradigms. Reasonable expectations for these TRLs involve packaged research, extensive literature review, and testing of partial proof of concepts. There often is an expectation that future groups may take information from this project and develop it into a more refined concept.

TRL 5–6—Primary expectations of these TRLs is a component or subsystem that can demonstrate measured performance to reach a goal, but potentially are not reliable. Key differences between TRL 3–4 and 5–6 are that design paradigms are set, and students conduct knowledge searches in a predetermined area. An example might be for TRL 3–4—'design a system relying on thermodynamic or electrically generated energy', whereas TRL 5–6 'design a system powered by an electric motor.' Because the level of uncertainty is much less than TRL 3–4, there is an expectation that solutions can move up far more quickly to TRL 7-8, as design decisions have more certainty of success in meeting metrics. Potential deliverables include sufficient professional documentation, videos of lab tests, as well as finished apparatuses that show proof-of-device or proof-of-component operation in a relevant environment.

TRL 7–8—Primary expectations should be for finished assemblies that work in a relevant use environment, and have some expectation, with refinement or parts replacement, of reliable final solutions. If space, time and finances are scaled appropriately, implementation should be expected. As an example, for many years, the first author has served as a source of sophisticated carts for transport of high-end nuclear non-proliferation equipment. These carts often have mechanical or electrically powered traverses, lifts and other devices for safely lifting expensive equipment. Such carts require students to move through Type 1–3 unknowns, but never contain Type 4 unknowns. Presence of Type 4 unknowns with a TRL 7–8 project is very likely unsuitable for a student capstone project.

4.2 Sample scoping statements

Sample scoping statements are presented in Tables 1-3 for previous capstone projects at TRL 3–4, TRL 5–6, and TRL 7–8. This is followed by an analysis of each scoping statement.

The underlying problem addressed in Table 1 is that cryogenic behavior of materials is poorly understood, and there is a need by this sponsor to develop a next generation testing apparatus that will advance understanding of essential components needed for this device. The goal of this project is clearly a TRL 3–4 project, with starting knowledge published in the cryogenic literature at TRL 1–2. One of the students assigned to this project will likely be a future graduate student who will use this device as the foundation of their graduate work.

The project outlined in Table 1 contains all four types of uncertainty. The class instructor had no experience with working with materials at cryogenic temperatures, and as such, any questions would have to be passed to the industry liaison, as well as the future supervising graduate professor (the second author on the paper). This implies time lags in information utilization that can easily get such a project off-track. However, there are solutions out there to many of the problems (such as how to seal the cryogenic chamber) and the project will challenge students to develop literature review skills in unknown information spaces. Will the project be successful if there is not a graduate student candidate on the team? This is not clear. However, restructuring of the deliverable to require design and testing of the device with potentially three seal types may be appropriate for a team without such a graduate student.

The mouse treadmill outlined in Table 2 is a system that must function in a lab environment. As such it is expected to achieve TRL 5–7. At the same time, without actual animal testing (due to animal testing paperwork), working out all system issues is unlikely. Under these conditions, this project would be TRL 5. There are various unknowns with the system, ranging from Type 1–4, though Type 4 unknowns (perhaps related to mouse behavior and psychology on the treadmill)

Table 1. Blue Origin Cryogenic Materials Tester (Example of TRL 3-4)

Title	**Apparatus for Cryogenic Testing of Materials**
Sponsor Profile	In November 2015, Blue Origin made history by being the first to successfully vertically launch, land, and re-use a rocket that went to outer space. Their New Shepard rocket utilizes the BE-3 liquid hydrogen and liquid oxygen fueled engine.
Context	The extreme loading scenarios of a launch and temperatures of liquid hydrogen (21 K, –420°F) place considerable uncertainties on material property data, when it even exists. Therefore, there is a considerable need for a load frame that can test materials, composite joints and laminates, under various loading scenarios while immersed in liquid rocket propellants.
Deliverables	Design and build a cryogenic testing chamber that will fit within one of WSU's load frames. The load frame selected must be based on client requirements. Measurement capabilities should include ultimate tensile strength, fatigue, tensile, and compression while immersed in liquid propellant. The device should be able to test multiple specimens, in conformance with ASTM standards, through a single cool down of the cryostat. The team will work directly with the project director at WSU and the Blue Origin liaison in Kent, Washington. The team will design and build a new experimental cryostat to fit within the selected load frame and create the environment necessary for the load tests. The team is expected to document their work, participate in regular status meetings, present their work as appropriate, and deliver a functional experimental system.

Table 2. Allen Institute Mouse Treadmill (Example of TRL 5–6)

Title	**Mouse Treadmill**
Sponsor Profile	The Allen Institute for Brain Science is dedicated to understanding mammalian brain function. One of the current efforts is focused on characterizing how the brain perceives, distributes, and integrates environmental information in order to make higher-order decisions.
Context	Critical to the success of this brain research effort is providing experimental mice the ability to run unencumbered while viewing visual stimuli and alter their running velocity in response to specific image features. Because brain function is being monitored with 2-photon microscopy while the mice are running it is imperative that the transmission of running forces to the mouse's head is minimal.
Deliverables	Create a treadmill prototype that allows at 15-30 g mouse to run unencumbered at various speeds. The treadmill should be able to run at a fixed incline, starting at 15 degrees. The apparatus should provide a direct readout of running speed and distance traveled, integrated with existing experimental hardware/software in the client's research lab (width $\sim$ 8cm, height $\sim$5 cm, length range 8–18 cm). The device should transmit sufficiently small running forces to the mouse's head so as to allow 2-photon imaging. This means that there should be less than 4 micrometers of motion in all dimensions at the imaging plane.

are minimal. Students had knowledge discovery aspects related to bearing selection and basic machining, as well as the higher types. The sponsor had given this project to another group of students at another university, who had failed at identifying key performance characteristics of the belt, so this group focused in on this aspect early. Mouse power output was unknown by sponsor, instructor and students, so students had to back-engineer an earlier device to estimate power loading. There was to be no power assist on the treadmill, which was a key requirement, and also introduced Type 3 uncertainty.

The treadmill should be small, and portable, and as such, can be transported by the students between the machine shop and the capstone lab. The device should cost no more than $2K to make. Students will collaborate with the primary contact at the Allen Institute, as well as a professor in the department who works on 3D printing flexible polymers. The team will work directly with senior engineering and project management staff within the Manufacturing and Process Engineering team at the Allen Institute for the duration of the project. The team will participate in developing project specifications, defining key milestones, and establishing a realistic development schedule. Technical assistance and project supervision will be provided by a Senior Mechanical Engineer. The team is expected to maintain a laboratory notebook to document all work, participate in regular project status meetings, present their work as appropriate and deliver a functional prototype, including engineering documentation.

The initial state of this project outlined in Table 3 is TRL 6, an existing prototype with restricted functionality in a relevant environment. The goal of this project is TRL 7–8, a working prototype qualified through operational testing. The task is reasonable for a group of four seniors, and basically involves implementing a well-understood technology (potentially a screw drive) to move the dewar up and down. Challenges for the students would include interfacing with the customer so any special

Table 3. Pacific Northwest National Lab Dewar Lifter (Example of TRL 7–8)

Title	**Nuclear Laboratory Dewar Lifter**
Sponsor Profile	Pacific Northwest National Labs works with the International Atomic Energy Agency in implementing the Comprehensive Test Ban Treaty. In order to do this, specialized equipment must be designed and manufactured to assist personnel in their mission.
Context	An important tool in nuclear material examination is gamma spectroscopy, with high purity germanium detectors (HPGe), which are used to accurately identify radioactive isotopes by quantifying the gamma ray 'signatures' unique to each radioisotope. Detection can be difficult when the target radionuclide (e.g., Pu-239; U-235) is in a sample with other radioactive isotopes. A Compton suppression system surrounds an HPGe gamma detector with a large sodium iodide (NaI) shield—an annulus and plug detector—which are used to suppression many of the interfering gamma events. The 'suppressed' spectrum results in a significant increase in detection sensitivity. PNNL recently placed an anti-Compton gamma spectroscopy system online at the Radiochemical Processing Facility (RPL) for use in nuclear forensics and safeguards analysis. The current design is pictured below. It was placed into service quickly with a simple manual lift table in order to meet operational goals.
Deliverables	What is desired is an improvement to the mechanical system for raising and lowering the HPGe detector. A motorized or electrical mechanical lift of sorts is envisioned, though a more efficient manual lift system is also acceptable. The lift should be able to handle a weight of 250 lbs, maintain a level orientation while raising/lowering, complete raising/lowering within a 5 minute period, run on 120 Volt AC or 12 Volt power, and stand ready to do as many as 10 cycles a day or 20 cycles within a week-long period. All electrical connections must remain intact during raising/lowering.

Table 4. Statistics for Capstone Projects Conducted Between 2012–15 (N = 94). Parentheses (#) enclose the number of projects observed at the reported level

	Average	Std. Dev.	Min	Max
Starting TRL	6	~1	3 (2)	8 (3)
Ending TRL	7	~1	4 (3)	8 (35)
Space Constraint	G	½ level	G (75)	G/Y (6)
Time Constraint	Y	½ level	G (7)	R (2)
Energetics	G/Y	½ level	G (53)	R (2)
Information Richness	Y	½ level	G (2)	Y/R (18)
Funding	G/Y	½ level	G (68)	R (3)
	Frequency Distribution			
Type 1 Projects	14%			
Type 2 Projects	40%			
Type 3 Projects	30%			
Type 4 Projects	16%			

requirements regarding space, etc. will be justified. It is expected that the students can complete a detailed specification with little customer intervention. Regarding understanding metacognitive scope, the unknowns are all Type 1 and 2 which increases the likelihood of TRL 7-8 success. One member of the sponsor's team is an experienced engineer used to making these types of devices. Space will be allocated in the capstone lab and a fully equipped machine shop is available to assist with construction. Up to $6K is available for fabrication costs. The students will collaborate with the primary PNNL support engineer, as well as the main client who is the lab manager for the HPGe cave.

4.3 Project statistics

In order to provide supporting evidence for the process described, data from 94 industry-sponsored capstone projects conducted between 2012 and 2015 were compiled to quantify (1) beginning and ending TRL levels for these projects, (2) resource assessment ratings, and (3) distribution in project uncertainty. We emphasize that this data is simply provided for comparison to exemplify project to project variability. Resource assessment was done on a 5 point scale with a score of 1 corresponding to GREEN, a score of 3 corresponding to YELLOW, and a score of 5 corresponding to RED. GREEN/YELLOW refers to a score of 2 and YELLOW/RED corresponds to a score of 4. Table 4 summarizes these results and provides insights about central tendency and variation within a design clinic.

Although the advocated scoping process precludes "red" resource allocations for projects, a few fell into this category, some to educate new faculty (the second author) on the scoping process. Several of these projects ended with mixed results and helped the authors to refine this heuristic. What the statistics also reveal is that the nominal outcome for a project is transition of subsystems readiness from a lab environment to a real-world environment. This corresponds to a TRL 6–7 level. Space is rarely an issue because this is immediately screened for design suite suitability. Time is sometimes an issue, but this can be regulated by deliberately over-scoping by no more than 20%. An acceptable fall-back position is always part of the client discussion. Projects are also picked for lab safety with most projects requiring only modest electrical infrastructure and hazardous waste handling. The projects are not simple and there is a fair amount of complexity in the information that needs to be managed by the project team and exchanged with the client. Sponsors are always learning things from watching and interacting with the students. Just over half the projects can be tackled by accessing knowledge possessed by students and faculty involved in capstone. Nearly 85% of the projects can be tackled by further integrating knowledge possessed by the sponsoring organization. A flat rate for design clinic projects along with a variable materials budget insures that projects are generally well-funded.

We emphasize that these statistics have led to a high rate of successful project completion (>95%) as determined by project sponsors. However, this system has evolved at our respective institutions over two decades of refinement. Results may vary depending on the cultures and practices at other institutions.

5. Conclusions

The TRL classification scheme is an easily understood tool for visualizing the initial and final state of a capstone project, facilitating dialogue between sponsors and instructors about appropriate deliverable expectations given project resources available. Capstone project scoping statements can be developed based on TRL analysis and accompanying resource assessment. Common formatting for scoping statements also facilitates project selection by students and assignment of project teams. For capstone projects with client-approved deliverables, a target TRL level of 5–6 coupled with access to Type 1 and Type 2 knowledge, is probably ideal. Under these conditions it is expected that design teams can identify a simplified operating condition, replicate this in a design suite environment, and credibly achieve a working prototype that meets customer needs. The effectiveness of the project scoping methodology described here is demonstrated through statistical analysis of capstone projects conducted over a five year period. Sample scoping statements that result from this project scoping methodology are also provided. To date, the methodology has only been used by the author team, but based on audience feedback from a project scoping and negotiation workshop at the 2016 Capstone Conference, it is ready for wider piloting within the capstone design community.

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