Research Maturity Levels: Implementation and Refinement of an online tool for Characterizing the Progression of Research

by

Melinda L. Liggett

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering
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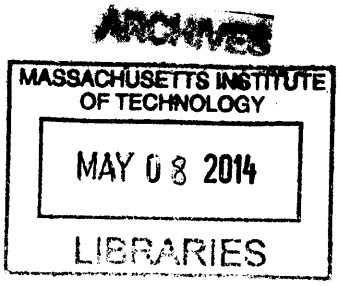

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Author **Melinda L. Liggett**
Department of Mechanical Engineering
December 2013

Signature redacted

Certified by **David R. Wallace**
Professor of Mechanical Engineering, MacVicar Faculty Fellow
Thesis Supervisor

Signature redacted

Accepted by **David E. Hardt**
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Graduate Officer, Department of Engineering

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- ○ intentionally
- ○ enthusiastically
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- ○ perplexingly
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Submitted to the Department of Mechanical Engineering
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ABSTRACT

Technology Readiness Levels are used in industry to help allocate resources, plan research and development, and clarify communication. Research Maturity Levels, proposed by Ming Leong in 2011, are designed to bring these same benefits to the academic research community. At its inception, the RML framework was accessible by a paper survey, and administrators of the survey could provide a visualization of research progress to respondents of the survey. In order to develop the survey as a helpful tool, the RML Framework was developed into an online tool. This enabled automatic visualizations and greater access to the framework. Discussed in this paper are the design of and findings from the online tool for the RML Framework.

For the tool to be useful, it must reflect the process of academic research, and the output from it can help researchers plan and communicate their work. Therefore, improvement of the tool falls into two broad categories: refinement of input (researchers translating their work to the tool), and refinement of output (researchers understanding that the tool says about their work). Interviews with researchers using the tool has lead to refinements including fewer difficulty levels for maturity levels, and inputting research impediments in comparison to one another instead of on absolute scales. Asking researchers about how and with whom they would disseminate tool data has led to proposed visualizations including long term research "shape" and short term comparisons between levels of progress. The next steps in developing the Research Maturity Levels framework are implementing these changes and additions, monitoring how the tool is used, and interviewing researchers who use the tool for further improvements.

Thesis Supervisor: David R. Wallace
Title: Professor of Mechanical Engineering

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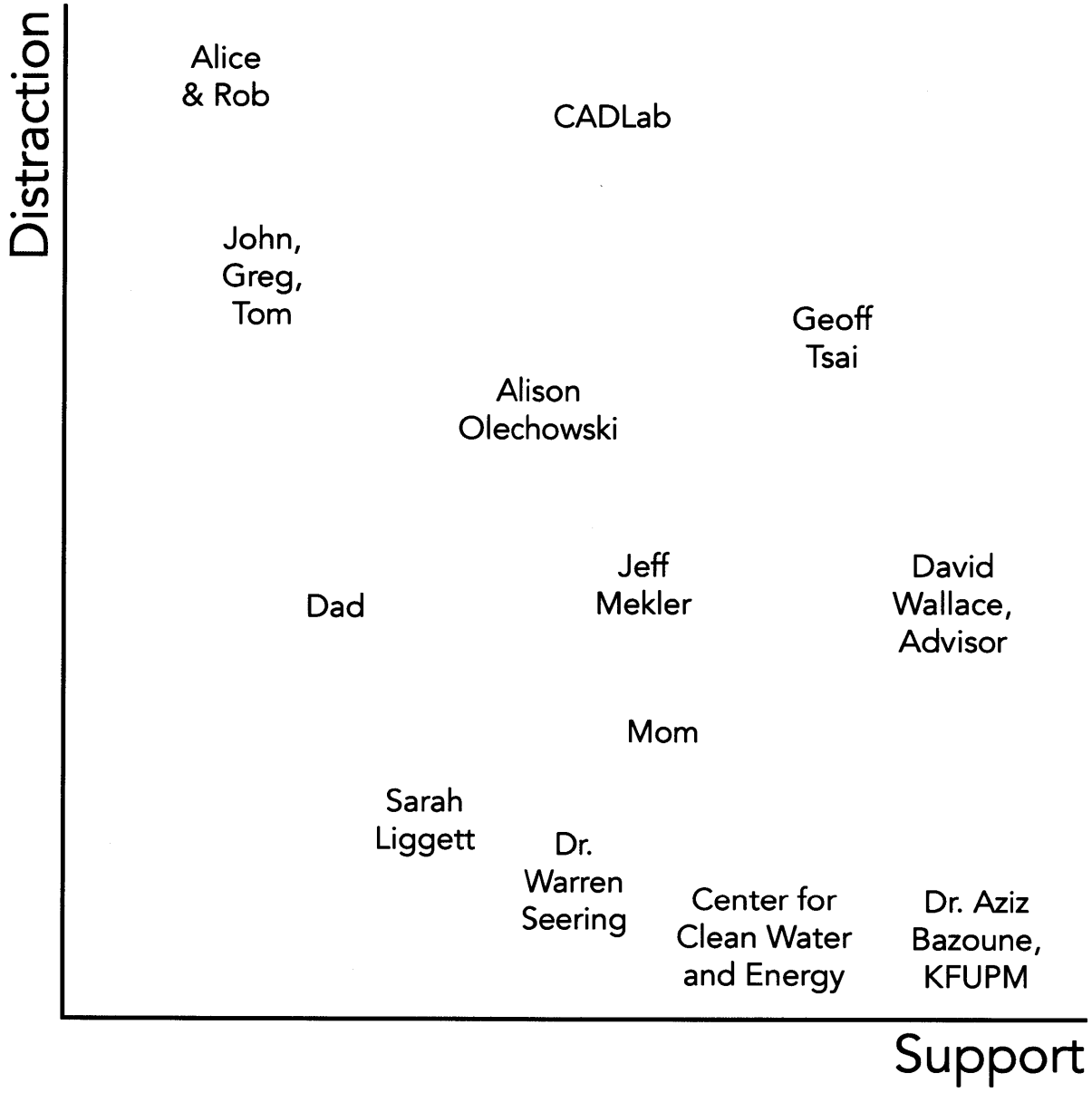

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INTRODUCTION

This paper discusses the online implementation and refinement of a framework proposed by Ming Leong in her 2011 thesis "Towards a Tool for Characterizing the Progression of Academic Research" [1]. Leong surveyed frameworks such as Technology Readiness Levels (TRL's) that characterize the process of product development, with the goal of making a similar framework for early stage academic research. TRL's in industry guide research and development processes so that resources can be better allocated and workers on the same project can better communicate. However, the industry frameworks were not applicable to academic research for several reasons: they require a tangible technology objective, have too low a resolution for academic research, and leave out components of successful academic research such as team formulation and background knowledge. Leong presented a framework called Research Maturity Levels (RML), which assesses the maturity of research projects to provide researchers with feedback which in the long term can provide insights into how academic research is conducted and how it can be improved. Her framework and an example visualization are included as Appendix B.

The RML Framework separates research projects into four areas: Background Knowledge, Problem and Question Formulation, Procedures and Results, and Resources. These four areas progress separately, and each has several maturity levels that are broken further into milestones to which respondents answer how far there are. For example, in the Resources area, one of the maturity levels is "Human Resources operational" and one of the milestones in that level is "Current research team trained and proficient in project skills", which follows the milestones of scoping and populating the research team. Milestones are written as descriptive sentences that characterize a fully mature research project (with the option of 'not applicable', since not all milestones apply to all projects). Respondents can answer along a spectrum from "not started" to "completed" to describe their progress toward a milestone. Respondents also input how difficult each maturity level is in terms of time they anticipate it will take to complete. For example, hiring graduate students may take less time than acquiring lab space or vice versa, and the RML Framework can reflect this difficulty. In addition to indicating research progress, respondents identify limitations and risks for their project. Respondents can link these impediments to one of the four areas, and rank them by how critical it is to overcome them. The framework is implemented as a survey that outputs a visualization of progress so researchers and stakeholders can more easily understand and discuss research progress. An example of this visualization is shown in Figure 1, with data source obscured for privacy.

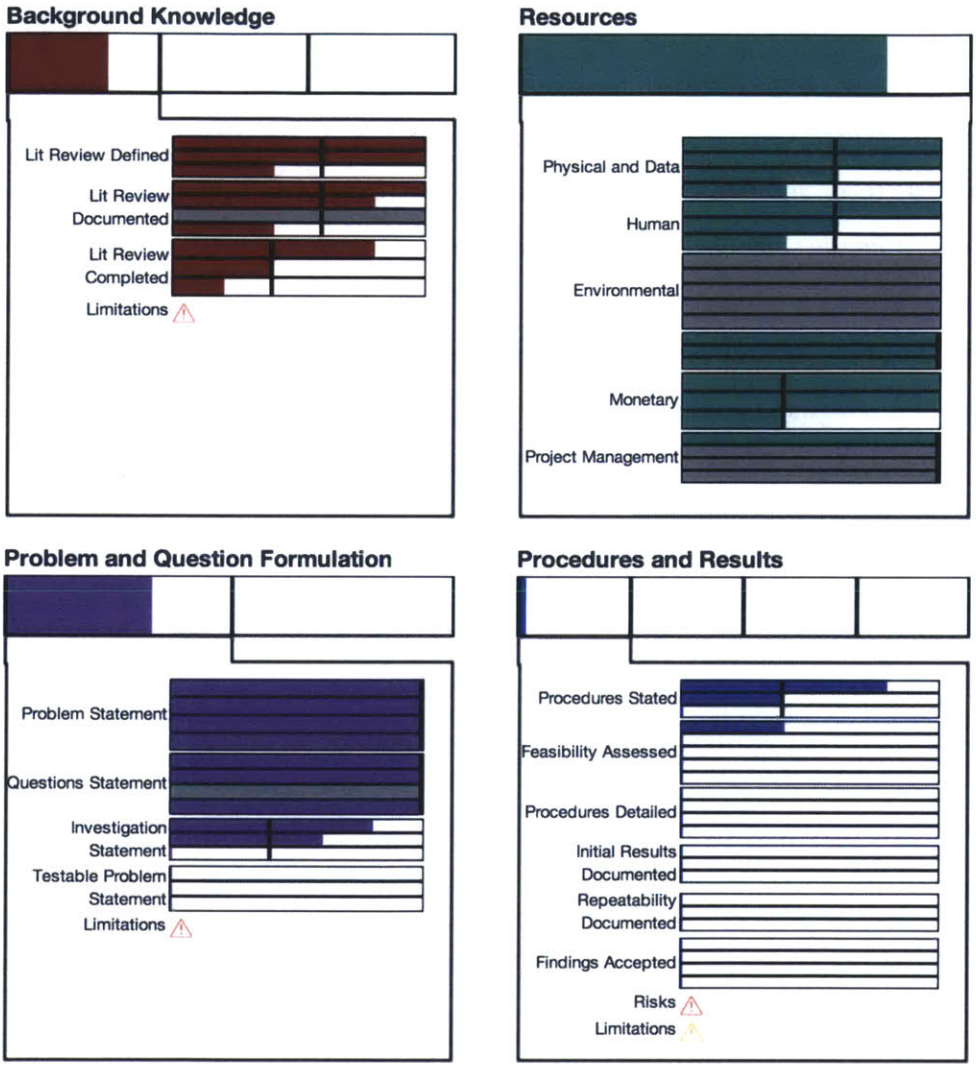

Figure 1: Example of an entire Visualization. This represents one point in time for a research project. This survey currently exists at rmltool.herokuapp.com

Leong's work ended with the definition of the framework, which was informed by many interviews, but it had not been tested as a survey or as a robust model for academic research. The Research Maturity Level framework is only useful if it describes academic research, will help research groups do better research, and

if it is accessible to the research community. The first step in testing and improving this framework was to put its survey online and automate the visualizations, allowing anyone with an Internet connection to use and give feedback on the survey and the RML Framework. This undertaking required a review of best practices for web and self-administered surveys. Once the first, simpler website was completed, researchers from MIT and KFUPM were invited to take the online survey and provide feedback on the instrument itself. These researchers were identified by their affiliation with the project; some had seen the paper survey before and some had not. Their feedback was incorporated in the database-backed version that currently exists at rmltool.herokuapp.com. This second version save all data, so researchers can return to their earlier responses to update them, and save an archive of the progress reports they had make (called 'snapshots'). The data gleaned from the second website is the basis for refining the inputs of difficulty and limitations and risk. Data from interviews with researchers are used to refine and propose new outputs from the survey. All refinement should lead to an RML Framework that is a reliable model for the process of academic research, whose visual analyses help researchers understand and better carry out their research projects, and whose data give insight into the process of academic research itself.

IMPLEMENTATION OF AN ONLINE SURVEY

The RML Framework has two goals: (1), to help researchers characterize and communicate their work to lead to better research projects, and (2), to provide insight through survey data into how academic research is done by examining what characterizes successful research projects, what models if any can describe academic research, and how the process of academic research differs among fields. Unfortunately, these two goals can work against each other. There are many factors that affect research, and the RML Framework wants to find which are predictors of successful research project. Without sufficient resolution, important insights may be lost. However, the need to increase resolution can make the survey too long and cumbersome, and deter researchers from using it in the first place. The current implementation of the RML Framework errs, if at all, on the side of higher resolution. The survey can be responsibly streamlined in the future as data indicate which questions are informative and which provide little information. It compensates for this attention to detail in two ways: employing methods of data collection that will have the lowest cognitive burden for the respondent, and providing visualizations at the end to clarify and simplify findings. For the goal of minimizing cognitive burden, a literature review of survey methodology and web survey methodology was conducted to understand best practices. Academic researchers should be willing to respond thoughtfully to a longer survey if it returns information that helps them plan a project and communicate its progress better than they could without the tool.

Survey Design and Research Maturity Levels

The online Research Maturity Levels tool is considered a "Self-Administered Questionnaire" because respondents fill it out without prompts from an interviewer [2]. Because an interviewer is not available to clarify anything for respondents, the wording and syntax of survey questions requires close attention. Some researchers have gone as far to recommend the maximum number of words in an English sentence at 16 [3], or 20 if the question extends over multiple sentences [4]. These questions should chose active over passive voice, and use specific nouns over pronouns [3]. Evidence also suggests that introductions of around 30 words can lead to higher quality answers for groups of questions about the same topic [5-6]. Questions should avoid vague words, especially those relating to time such as 'frequently', 'usually', or 'regularly' [7]. Instead, specifics should be given such as 'more than three days a week' or 'two times a month'. Specific wording will also help RML researchers compare data across research projects without worrying about interpretation.

Even if questions are concise and specific, respondents may still need clarification. A review of literature suggests to the author that respondents must know help is available, and they can access help with minimal effort. For example, one study examined how respondents used definitions within survey prompts, comparing the effectiveness of definitions places within the question to definitions places in rollovers. Results showed that respondents were more likely to read the definitions when they were within the questions, but that they read definitions more carefully if action on their part was required to get the definition (i.e. moving the mouse for a rollover) [8]. Other tools to reduce cognitive burden include the layout of the survey. Layout choices affect how respondents move through the survey, and whether the next steps are clear. "Semantic chunking" is placing questions about the same topic together [9-10], and can reduce the paging necessary to complete a survey.

Considerations have also been given on how to collect reliable data. "Primacy" or the "primacy effect" is the phenomenon of respondents choosing the first choice to an answer [8]. This effect sometimes occurs because the first answer seems good enough and the respondent doesn't read the rest of the options. It may be because they want to navigate quickly through the survey (known as "speeding") [11]. Efforts should be taken to prevent respondents from speeding and to influence them to read all responses before deciding. One way to combat speeding and primacy is to remind respondents of the value in filling out the survey accurately by stressing the incentives of the RML Framework.

Various incentives can motivate people to take surveys. Often, incentives are included with surveys to procure a larger data set or to engage respondents who are not interested in the survey topic, in order to avoid the bias in a data set generated only by respondents who are interested in the survey topic [12]. One study looked at placing a very interesting question at the beginning of a survey to incentivize people by piquing interest [13] while another looked at the effects of money-based incentives [14]. Most studies are interested in getting a relevant cross section of the population, especially when the data procured are meant to apply to the population at large. The goal for the dataset gathered using the RML Framework is to apply to the academic research community at large, but at this early stage, the primary objective was to father data to test the survey design and the implementation interface. For the RML Framework, the visualizations and the value provided by them are the incentives themselves. The visualizations are considered an "extrinsic, self" motivation, which compared to other motivations, leads to the lowest response rates [15]. Therefore, in addition to touting the visualizations as the survey incentive, the survey can also emphasize that more data in the RML Framework leads to a better understanding of the academic

research process as a whole, which could be considered an "intrinsic, other" motivation [15]. As data accumulates, certain research sectors may not be well represented, and incentives should be investigated for how to get a better cross section of the academic research community. For now, survey respondents receive the visualization and knowledge that they are contributing today to a better research tomorrow.

One last consideration for the survey was whether to include a progress indicator, showing how much of the survey was completed and how much was left. Evidence of the usefulness of progress indicators has been mixed. While one study may show no difference between surveys with progress indicators and those without [16], another shows lower completion rate with a progress indicator [17], while another proposes that in the absence of a progress indicator, respondents may give up not knowing how much more time the survey will require [18]. Looking at the literature for long surveys (of which the RML Framework is one) reveals more helpful data and shows that progress indicators help only when they are in line with the respondents' assumptions about how long the survey will take. Progress indicators increase completion rates for a task that is shorter than promised and decrease completion when tasks take longer than expected [19]. For the RML Framework, the same survey is filled out many times. Respondents should become familiar with the survey and understand its length and thus adjust their expectations. They are also reminded that they can save data at any time and return to complete the survey later. This feature should cut down on survey abandonment since researchers can leave and return to the survey without losing data. Lastly, the visualization is available as respondents fill out the survey. It changes in response to survey data and acts as a progress indicator that respondents can choose to see or not. Combined, these features (clear question wording, clarifications, semantic chunking, incentives, and progress indicator) should prevent respondents from abandoning the survey.

Web Development and Design

In this section, current implementation of the survey will be shown and discussed. Where applicable, the first implementation will also be shown for contrast, though the first site is now considered deprecated. Some aspects of survey design were intentional while others can be changed without harm to the survey. Future development of the survey will benefit from knowing which features should stay the same and which can be changed.

The first implementation of the survey was as a static .php-based website with automatic visualization and

no database. This implementation was used to test the framework with survey respondents to determine whether the questions made sense and whether the visualization was valuable for them. The current site is database backed. Researchers can create an account and add their research projects. For each project, they can update and save their progress. At any time, they can archive this progress, which is called a 'snapshot' because it represents one moment in time. These data are catalogued, and researchers can continue to update their projects without re-entering data they have already given. Researchers can review their research progress as one journey, and the snapshots are data that are documented along the way. A list of tools used to create and run the websites is found in Appendix A, "Programming References".

The bulk of the website is the survey. When respondents want to update their project progress, the survey begins on the "Resources" tab, though they can move freely among the sections and there is no set order. Within each of the four major sections, there is a question order that goes from top to bottom. For this reason, the four sections are given as four tabs at the top of the survey page, and each is a long page of questions. The top of the survey page is shown in Figure 2 below. This section was kept the same between first and current implementations of the survey.

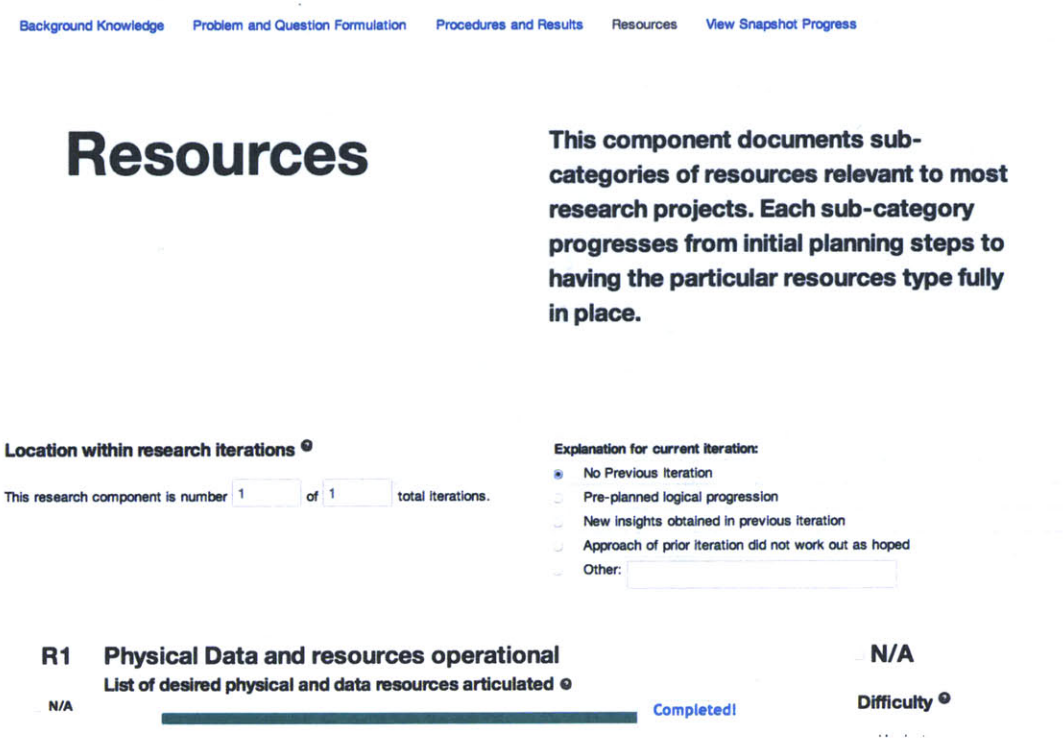

Figure 2: Survey page showing the Resources section open. To the left are the other four sections, and the right-most tab opens the Snapshot Visualization.

Each of the four sections has an explanation at the top. Each section also has a field to input iterations. The RML Framework introduced the notion of iterations, absent from TRL frameworks used in industry, to reflect the iterative nature of academic research. Multiple approaches may be anticipated and are considered separately so that one iteration can be completely finished, but the overall project is still in progress as new knowledge leads to reiteration of the research process. The "Procedures and Results" section has a part for researchers to input their process – whether it is simulation and theory based, or based on empirically-based evidence – their hypothesis, and the current process they are using. "Resources" has a green color scheme, and other sections have different colors that are also used in the Visualization. These colors are for visual differentiation and are used in visualizations to refer to the four sections, but they were chosen arbitrarily and can be changed if that leads to better visual analyses.

After the introduction, each section has its maturity levels and corresponding milestones. Milestones are given as assertions that will be true of a mature academic research project, and respondents indicate how close they are to reaching these milestones. Figures 3 and 4 show what a maturity level looked like in both survey iterations: .php (no database), and current. The length of the RML Framework makes it impractical to write out all clarifications within the question text so rollovers were chosen instead as shown in Figure 4. Users will also become familiar with the survey over time, so putting clarifications may at first be helpful but later become hindrances if users do not need them.

Physical Data and Resources

This sub-category is related to tools, equipment, hardware, data sources, case studies, etc. required for research.

Maturity Level	*Not started*	*Less that half*	*About half completed*	*More than half*	*Almost completed*	*Completed*	*Not Applicable*	Milestones	Notes (optional)
R1 Physical Data and resources operational	○	○	○	○	○	○	○	List of desired phyrical and data resources articulated	
	●	●	●	●	●	●	●	Sources or physical and data resources identified	
	○	○	○	○	○	○	○	Physical and data resources in place	
	●	●	●	●	●	●	●	Physical and data resources tested, de-bugged, and surveyed	
Overall	○	○	○	○	○	○	○		

Figure 3: The R1 Maturity Level on the .php site. The design allowed for smaller space, but the radio buttons were burdensome. There were no clarification rollovers.

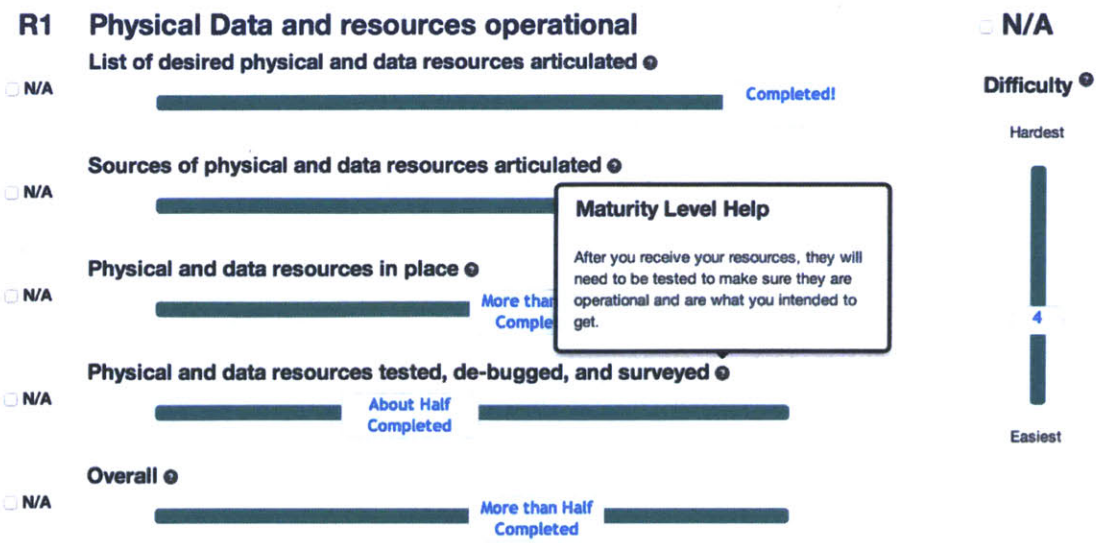

Figure 4: Current R1 Maturity Level, displaying a clarification rollover. Rollovers exist for all sections: milestones, difficulty, limitations & risks, iterations, and procedure.

Although the first iteration's survey took less page space, radio buttons proved difficult to use. A slider bar was more intuitive to use for respondents, as the text changes while the slider moves along the track. A slider is also similar to how the data are displayed in the visualization at the end. Clicking 'N/A' grays out the section that is not applicable, and 'N/A' on the top right will gray out the entire maturity level. Figure 4 shows difficulty next to the maturity level, while Figure 3 does not have it. In the first iteration, as in the Framework proposed by Leong, difficulty of maturity levels was done at the end of each section. This change will be discussed in the 'Refinement of Input' section.

Each of the four sections also has input fields for Limitations and Risks, factors that are delaying research progress. Respondents name the impediment and indicate how critical it is to overcome this limitation or risk: low, medium, or high. This feature is shown in Figure 5 on the next page.

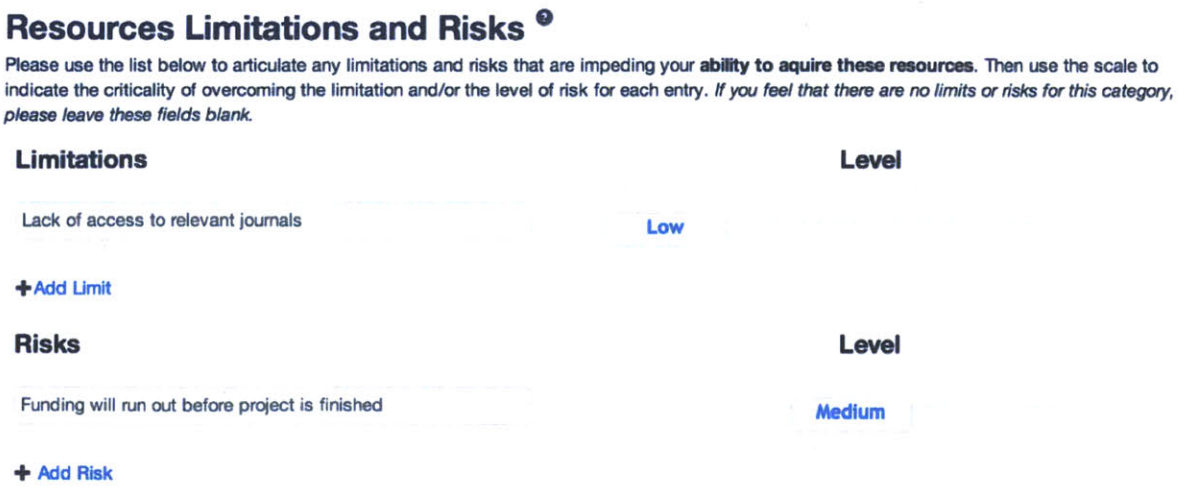

Figure 5: Inputting Limitations and Risks. Limitations and Risks are not required and can be added to any of the four sections.

For each maturity level the milestone progress is shown as a green bar. The thick vertical bar for each maturity level indicates the overall level of progress. Any milestones indicated as 'Not Applicable' are disables in a low-contrast grey. For these figures, the height of a milestone indicates difficulty, though this may be changed and is discussed in the "Refinement of Output" section. The progress bars have rollovers to remind the respondent what they represent, as shown in Figure 6. In Figure 7, the progress for Background Knowledge is shown as the first of three iterations. In this case, a limitation was entered and the user can rollover this symbol to see what they had entered. The symbol changes color based on the severity of the limitation or risk. Figure I shows what an entire visualization looks like on the site.

On the current site, users of the RML Framework can access archived data and visualizations from their own homepage for later reference. The site also contains pages explaining what the RML Framework is and its theoretical underpinnings, though it is designed to highlight the survey instead of the theory behind it. It is an evolving site, and data from its current users are shaping how the survey inputs and outputs data, to provide the most helpful visualizations while revising the survey to be as short and easy to take as possible. The research team conducted sixteen interviews as respondents went through the RML Framework, because there is value in seeing respondents interact with the computer and questions [20]. By the end of most interview, the respondents had made an account, and some used the tool again to save progress data on their projects. These data were used to refine the inputs of the survey.

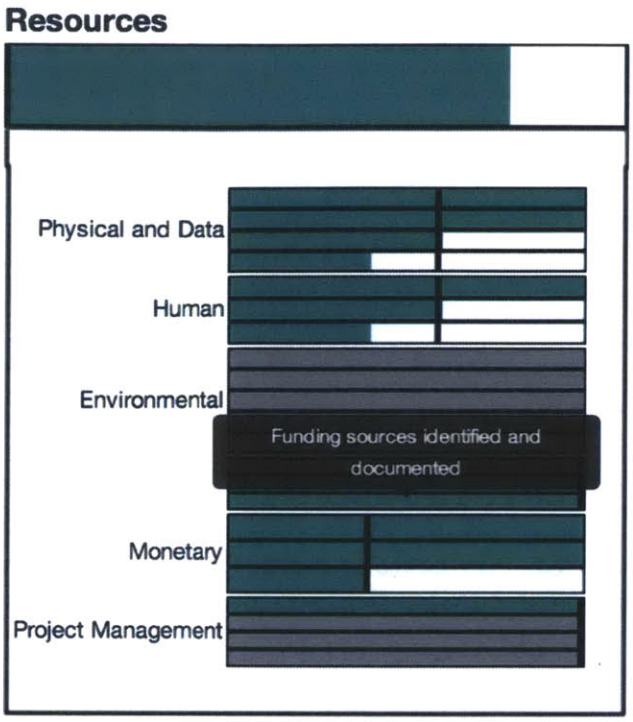

Figure 6: Snapshot Visualization for Resources. The height of the bars represent difficulty, and each has a rollover to remind the researcher that that section was.

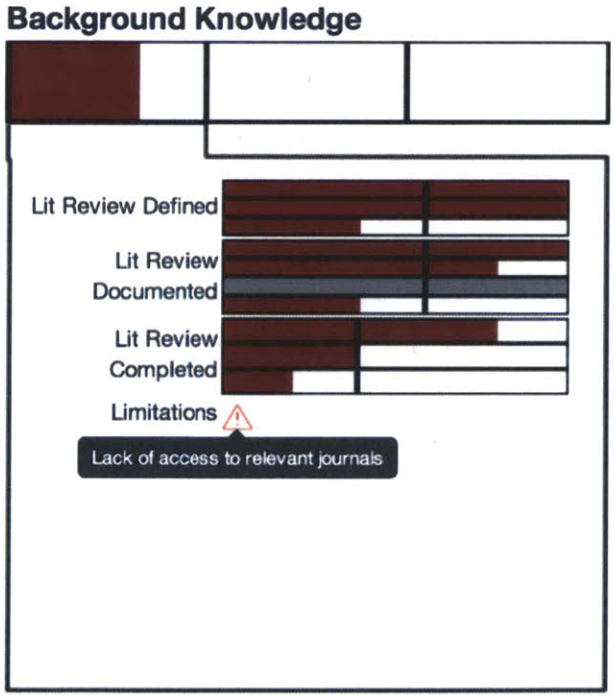

Figure 7: Snapshot Visualization for Background Knowledge, showing a limitation rollover. This user is in the first iteration of an anticipated three.

Research Maturity Levels - Summary Report

Project: Example
Objective: Example
Deliverables: Example
Principal Investigator: Example
Snapshot: 01 July 2013

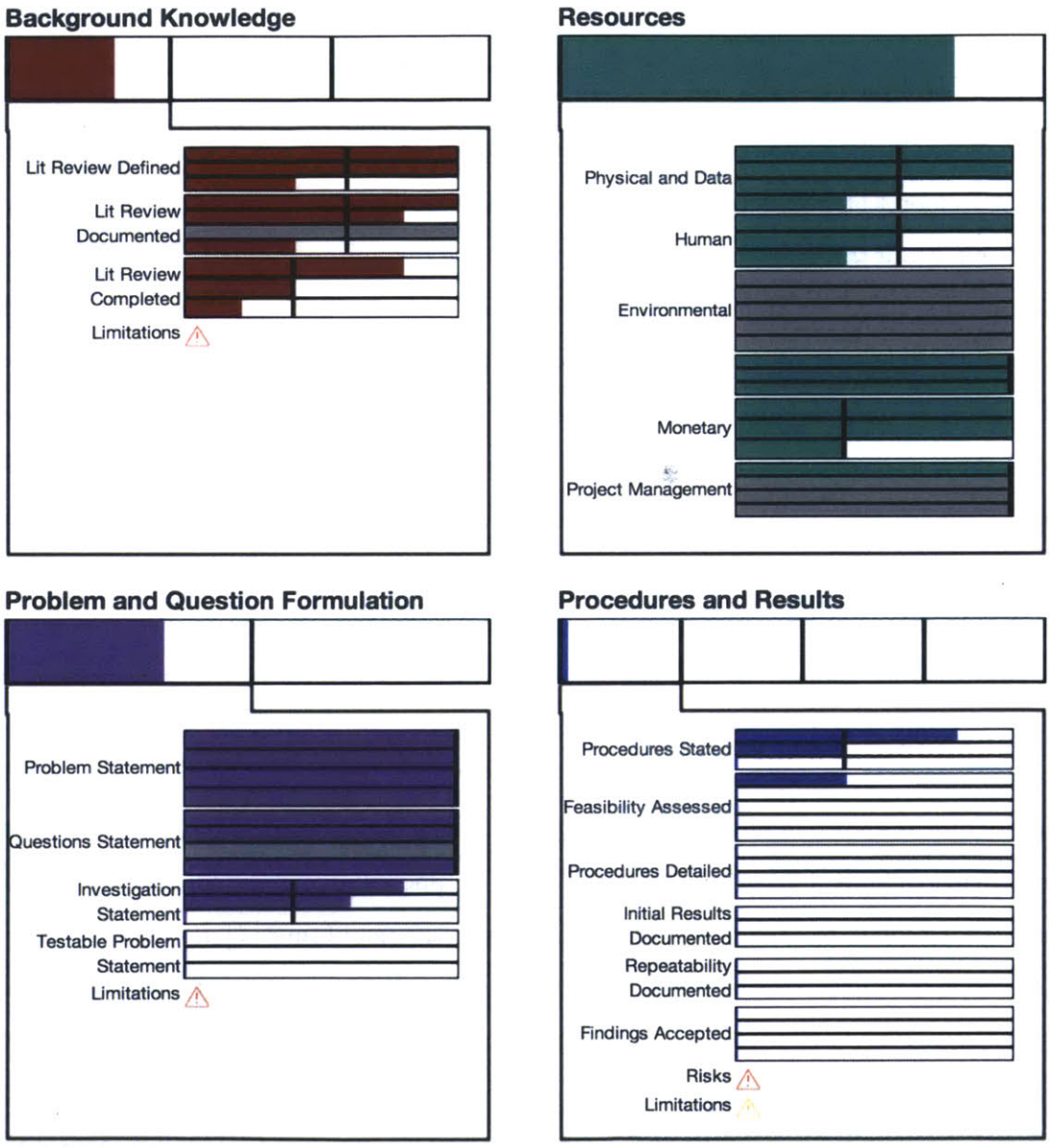

Figure 1 (REPRINT): Example of an entire Visualization. This represents one point in time for a research project. This survey currently exists at rmltool.herokuapp.com

REFINEMENT OF INPUT

The RML Framework receives information from researchers to presents their research progress in a meaningful way. For the visual analyses to be meaningful, the data that creates them should accurately reflect what is going on in the research project. The inputs of difficulty and limitations and risks were considered for improvement.

Difficulty

In the first iteration of the survey, difficulty of maturity levels was its own part at the end of each of the four sections. Respondents referenced previous answers to the milestones, remembered that maturity level, and input how difficult they thought it was. Respondents had to think about each milestone at least twice instead of inputting all information about it at the same time. The RML research team considered this method a greater cognitive burden than asking for difficulty when milestones are being filled out and moved the Difficulty input field to each maturity level accordingly. The current survey has the heading "Difficulty" above a vertical 1 to 10 slider bar. An explanation rollover tells the respondent that difficulty corresponds to time it takes to complete this maturity level, not something like "mental effort" or "skills necessary to complete," to help instruct respondents on how to use the scale. The difficulty was put as a vertical slider bar instead of a horizontal one to differentiate from the progress slider bars for each maturity level. Each difficulty bar is placed to the right of its maturity level's progress slider bars to imply that it refers to that maturity level, as shown in Figure 4.

The difficulty scale is known in survey methodology as a Rating Scale and could be loosely interpreted as a Semantic Differential Scale if "easy" and "difficult" were at opposite ends of the spectrum and the middle was interpreted as neutral, meaning it takes about the average amount of time [2]. In interviews with respondents using the survey, several respondents expressed that the number was arbitrary and would describe the maturity level as "this takes a long time, make it 10" or "this one is very simple, make it a 3 or 4," implying that the scale has too high of resolution for what was necessary. From survey completions, there were 494 data points for the difficulty of a maturity level between 1 and 10 (non-responses are '0' and were not included). One would expect an even distribution of these values, but the data showed that a quarter of the responses were "5", and the next common were "3" (17%), "2" (12%), and "7" (10%). Only 1% of responses were for "9", though 7% were rated a "10", which implies that respondents wanted to express "most difficult". For all respondents, only 8 projects had more than 30 difficulty data points.

On average, those survey respondents used six different maturity levels. In those eight projects, six had two "prominent" difficulty levels, meaning two levels were used more than the sum of time the rest were used. In two projects, one difficulty level was used more than the sum all over levels were used. These data imply that the 1-10 scale is too high a resolution.

A numbered scale also implies that all respondents will interpret the numbers in the same way. This is a problem within research projects, and especially between them if RML researchers want to look at which maturity levels take longest to complete. Instead, a timescale might be considered. Instead of numbers, respondents could input "takes 3 weeks" or "takes 3 months". This revision would help calibrate within and between research groups. However, it presents another pitfall. This method implies that respondents know how long maturity levels take, and even to the resolution of weeks or months. Meaningful time scales can't have greater resolution than that of respondent estimation. The timescale also does not take interruptions into account. A task could take three weeks if worked n exclusively but three months if team members are one vacation, or have to go to a conference. Both the 1 to 10 scale and timescale methods were misleading.

In determining how respondents will indicate which maturity levels take the longest, it is important to understand what is desired by a difficulty scale to determine how respondents should input this information. In the framework, the difficulty specifically refers to time that the maturity level will take to complete. Respondents should be able to input this datum as it gives a better picture of research progress and process. Though the data here are from a small sample, combined with the interview data, there are compelling reasons to change the difficulty scale: to making it smaller and moving away from an objective numbered scale. A smaller scale could make a less overwhelming survey and lead to less error of respondents using the same number and meaning different degrees of difficulty.

Instead, difficulty assessment should be done in comparison, with maturity levels placed along a spectrum from "least difficult" to "most difficult" for each project (or "least time-consuming" to "most time-consuming," to be more specific). Instead of evaluating each maturity level for estimated time, then comparing that to the estimated time for another maturity level, respondents ask "Which will take longer?" and sort accordingly. Problems arise when two maturity levels take comparable length. At this point, to order them implies a resolution that the respondent does not have.

Ordering the levels into larger "bins" was the best option. Maturity levels are compared, but this method does not require a high resolution of choices. In survey methodology, the number of choices is generally recommended at 5 (maximum for no visual aid) or 7. An odd number of choices gives the respondents a "neutral" option, while an even number forces them to choose a side. Since difficulty is an input that can be compared to other maturity levels, difficulty should be its own section so the respondent can consider all maturity levels in one section at the same time. This move back to the original survey (difficulty as its own section) highlights the importance of testing out the site with users. A proposal for this interface is shown in Figure 8 below.

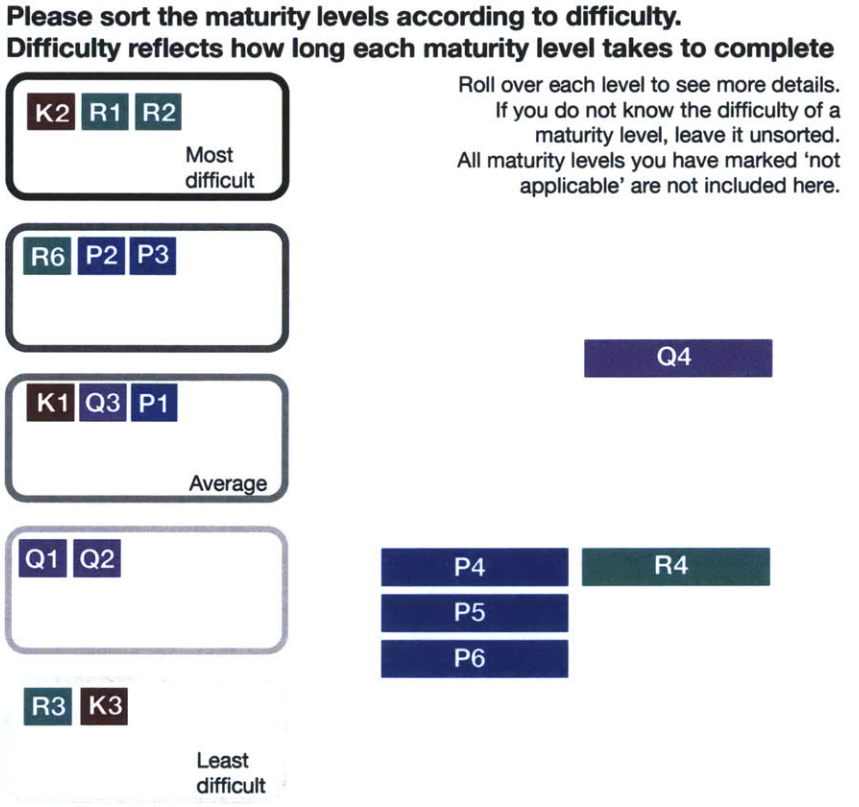

Figure 8: Proposal of how difficulty is input into the RML Survey. "Not Applicable" maturity levels could be shown in gray, and rollovers should remind users what each maturity level is. This sorting is for the current iteration. Those sorted are in the bins on the left, the unsorted ones are on the right.

Limitations and Risks

Each section in the survey has a space for respondents to list any limitations and risks hindering research progress. Currently, respondents can list them in the "limitations" or "risks" part of each of the four sections, and indicate severity: low, medium, or high. The survey defines the severity as "criticality of overcoming the limitation and/or the level of risk for each entry," as shown in Figure 2. The RML Framework splits factors impeding progress into two categories: limitations are factors that slow down research progress (like insufficient time on a tool), whereas risks are events that can stop research entirely (like a tool breaking).

In interviews with survey respondents, the low, medium, high scale seemed sufficient. No respondents expressed an inability to choose between levels, which would imply that there more levels of difficulty on the survey than respondents see in their projects. The data show an uneven distribution with more "high" severity risks and limitations reported. This trend may be because there is a threshold of severity that has to be reached before a limitation or risk is worthy of being listed and deserving of space on the visualization page; respondents are not as likely to identify impediments they see as "low" severity.

Data indicated another metric that merits further research: the amount of influence the group has over these hindrances? For example, two limitations were entered for different projects, both at a "medium" severity level. One was, "local industry might not be interested," and the other "lack of access to industry and proprietary data". Both fall under the "information" category, and both are apparently medium severity. But there is a potentially large difference between them: the group's ability to change these limitations. The RML Framework should reflect this difference.

The survey data set, at time of this publication, included just fewer than 100 limitations and just fewer than 80 risks with severity values. The difference in quantity is likely due to primacy effects, that "limitations" is placed above "risks" on the survey and respondents list these factors in the first field. All risks and limitations were categorized into one or several of the categories: time, money, people/hiring, information, tool limitations. They were also categorized according to the intended definitions of limitations and risks. Though survey respondents were clear on the idea of severity, they did not differentiate limitations and risks the way the RML Framework intended. There was no significant difference between risks and limitations either for the categories or the intended meanings. The lists may be

meaningful to the research team themselves, but the designations do not lead to better understanding of the research process if a distinction between limitations and risks is assumed but are nor reflected in the data. This finding indicates that the input method for this section should be revised.

Though the severity scale works, the current input method for limitations and risks does not generate meaningful data for the RML Framework. One solution is changing how these hindrances to research are input into the survey altogether. Once again, it helps to think about the data desired, to determine how they should be input. In order to better understand the progression of academic research, it is important to know the factors that hinder it. Possible characteristics that might matter include how critical it is that the impediment is overcome, what the hindrance concerns (time, money, weather, staff, etc.), how long it affects the research (constant pressure vs. hindrances that occur briefly), how much control the research group has over the hindrance (possibly characterized as time the research group could spend to remove the hindrance). As always, tracking many characteristics is more helpful for understanding the relationship between hindrances and research progress but multiple characteristics can deter people from inputting data if the process is cumbersome.

Because respondents have had trouble distinguishing between limitations and risks, the survey should move away from these words and focus on the intended meaning behind them by identifying what is slowing research progress, how critical it is to overcome it, and how much influence the research team has over it. How long the hindrance affects the research project and what it concerns (time, money, etc.) can be gleaned from the data and do not need to be input by the survey respondent. Eliminating these factors will decrease burden on the survey respondent. A proposed "Impediment Input" is shown in Figure 9. The new input method should help users categorize and identify factors and events that limit progress. The input method also mirrors how hindrances are displayed, which should help survey respondents understand the visual analyses that derive from the survey.

Research Progress Impediments

It is good when looking at research progress to consider the things that are impeding progress. These can be things that slow down research, or are able to stop it altogether. Please enumerate them below.

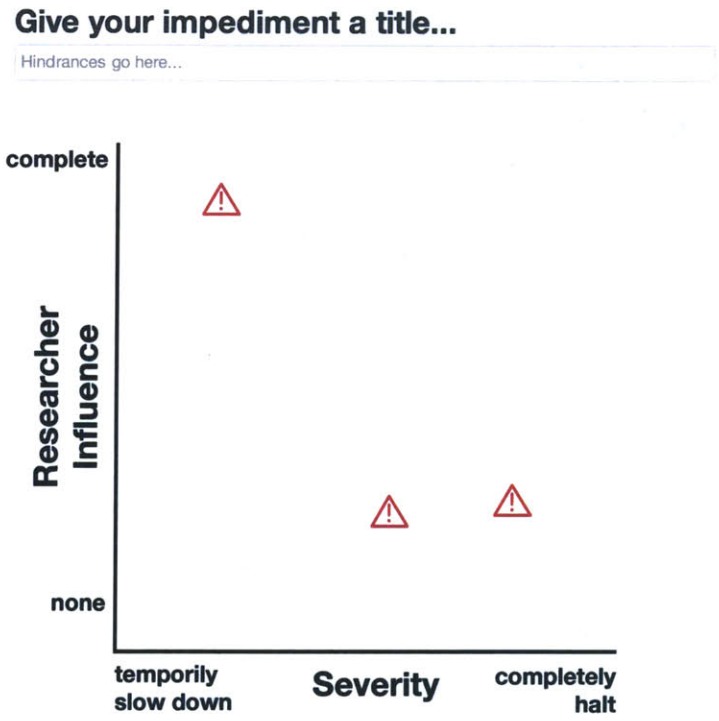

Figure 9: How Limitations and Risks could be input. User gives a name to their impediment then drags it to the chart below. Information about other impediments could show up if user drags one close to it. This input method makes the limitations and risks more comparative than absolute.

REFINEMENT OF OUTPUT

This section discusses the current visualization supported by the survey, refinements for it, and proposes ones that might be added to future iterations. The current visualization was proposed in Leong's 2011 Thesis. Other visual analyses come from interviews with users of the RML Framework who explained what they would want to see from the survey about their research projects. The visual analysis of data should foster honest communication within and outside a research group, allow researchers to understand and explore their data, and honestly reflect the current state of research. Perhaps, researchers who see the visualization of another research project may decide to use the RML Framework themselves because of the value of the visual analysis. Therefore it is important to consider the data and guidelines for presenting it, to create the best visual analyses possible.

Visual Analysis Best Practices

Data can be classified into one of four categories: nominal, ordinal, interval, and ratio [21]. These categories affect the best way to display the data. Nominal data do not have an order, and are usually described by names. Nominal data are often presented in a table rather than graph, and color-coding is not in a sequential scale because placing it along a scale implies an ordering. Ordinal data do have order and can be placed along a scale; such data are often presented in charts and graphs, with sequential color codes to imply the ordering [22]. For example, in the RML Framework, limitations and risks are nominal, but their severity is ordinal. Likewise, difficulty is also ordinal. Progress is also ordinal, as maturity levels could be placed along a spectrum from "not started" to "completed." Interval data consider the distance along some attribute's scale and compare two data points. Interval data are reflected in attribute scales whose degrees are well-defined (like temperature) but can be used in RML when considering progress between two snapshots. Ratio data is like interval data but has a clearly defined zero point [21]. The RML Framework currently has no ratio data types. However, future metadata (comparing number of limitations to risks, e.g.) is ratio data, and future RML researchers may want to investigate that and provide visual analyses for ratio data.

One common theory of visualization has been summarized as as "overview, zoom and filter, details on demand" [23]. This refers to an interactive visual analysis, where the displays can change as the user requests. While the website can support these changing visualizations, the site should also support static visualizations that can be printed and sent to team members or other stakeholders. Consideration will be

given to what the static and dynamic versions of visualizations should be. In all visual analyses, "Displays of evidence implicitly but powerfully define the scope of the relevant." [24] Each visual analysis should have a specified goal of what it is displaying, and this goal should be worthwhile for academic research (showing progress vs. rainfall, for example, might mislead researchers on what is important for research), and the visualization must not show data in a way known to be confusing or misleading.

Research Snapshot Visualization

The RML Survey, at time of publication, supports one visualization called a "snapshot". It is the research progress at one moment in time, as proposed in Leong's Thesis (2011), shown in Figures 5-7. This visualization should fit on one printable page, and indicate the current state of the project. This overall visualization shows iterations for each section, each milestone's progress and difficulty, and the existence and criticality of limitations and risks. The visualization organizes this information in the four sections, shows milestone progress in charts known as bullet graphs, and lists limitations and risks underneath.

Showing progress and difficulty of maturity levels in the same graph has proved troublesome. Progress makes sense as length of the bullet chart, and this output method matches the slider bar input method. Difficulty can be shown as the horizontal length of the bullet (easier levels are shorter; harder ones are longer). However, this removes from the visualization the ability to easily compare the progress of multiple levels. If left justified, easier maturity levels that are complete look similar to harder maturity levels that are not yet completed. If right justified, the bullet graphs imply that easier maturity levels were started after the harder ones. These options are shown in parts A and B of Figure 10.

In the current visualization, more difficult maturity levels are taller, as shown in part C of Figure 10. This graphic was selected because the previous two visual analysis methods use horizontal distance for both progress and difficulty, which can be confusing. With the height method, difficulty cannot be compared directly between levels, and it is hard to differentiate between close levels of difficulty. Another option is having color indicate difficulty, as shown in part D of Figure 10. Difficulty is ordinal, so changing the saturation or brightness can be used to indicate degree of difficulty. Easier levels are lighter, while more difficult levels are darker. It is possible this method may lead to very busy graphics that seem to 'blink' because some sections are light and some are dark. There is also a limit to distinguishable values. Lastly, because the four sections employ different hues, maturity levels of identical difficulty will not look the

same in different sections, making comparison tricky if not impossible. A comparison of these implementations and a chart summarizing advantages and drawbacks are shown in Figure 10 and Table I below.

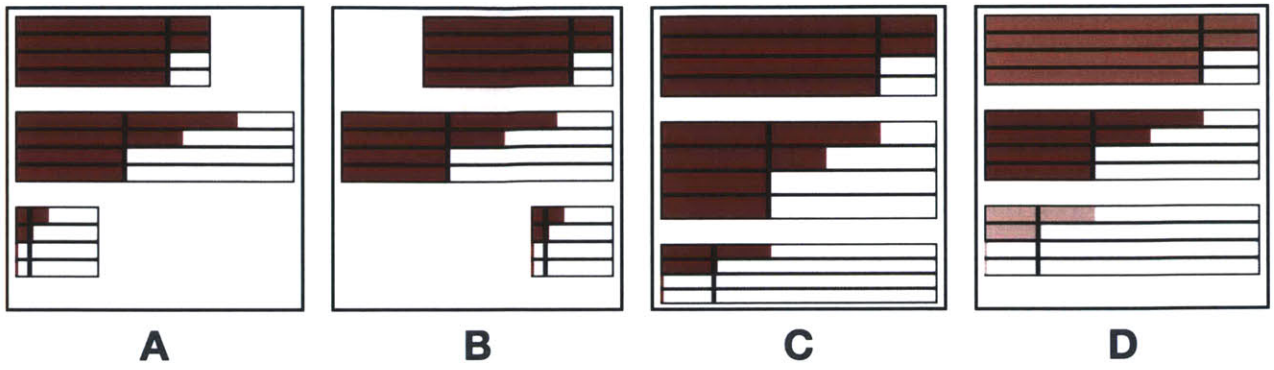

Figure 10: Four methods of Snapshot Visualization to show Progress and Difficulty. Every graph represents the same raw data.

	A	B	C	D
Method	Bar length, left justified	Bar length, right justified	Bar height reflects difficulty	Colors reflect difficulty
Advantages	Better visual comparison of difficulty	Better visual comparison of difficulty	Better visual comparison of progress	Better visual comparison of progress
Drawbacks	Progress cannot be directly compared between levels. Completed easier levels look like uncompleted more difficult ones.	Progress cannot be directly compared between levels. Complete	Difficulty cannot be directly compared between levels; Users may not interpret height as difficulty.	Hard to telling similar colors apart; difficulty cannot be compared across sections; users may not interpret color as difficulty.

Table 1: Advantages and Drawbacks to the Display Methods in Figure 10. No visual analysis is ideal, and the real effects of these drawbacks and advantages should be found by testing these visual analyses with users instead of assuming which visual analysis is best.

Displaying progress and difficulty in one visualization works if both concepts can be understood, but not if either of them is compromised. None of the four options presented allow progress and difficulty to be understood and easily compared across maturity levels. One last option is that this visualization does not display difficulty at all. Difficulty speaks to the rate of progress over time, and the snapshot is one moment in time, so it is not essential that difficulty be displayed to understand one moment in time. Difficulty could be one of the "zoom and filter" options. An example of an interactive graphic, where the user can choose which difficulty level to highlight is shown in Figure 11. For the static/printable view, users would have to choose which difficulty they want highlighted, or choose that multiple degrees of difficulty are shown in different colors.

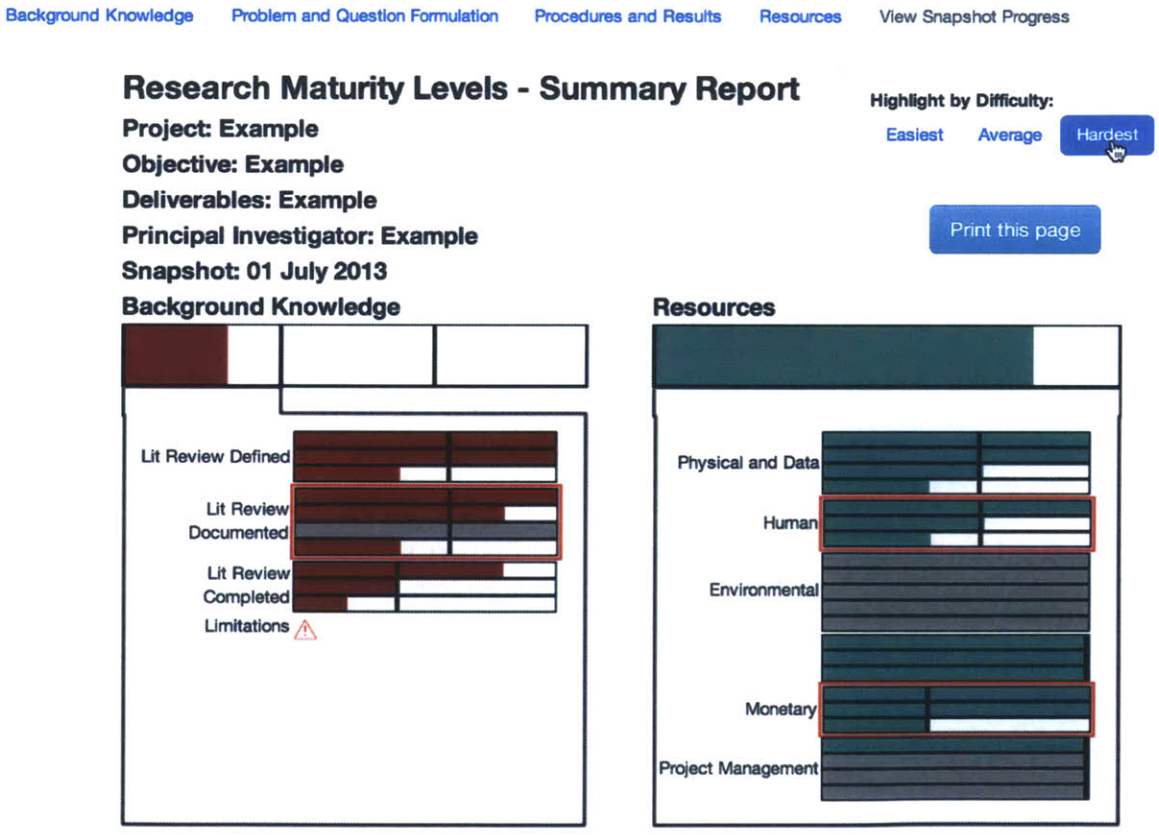

Figure 11: Interactively displaying difficulty, showing only the top two sections. The user would choose from the same number of difficulty levels in the survey; ex: if there are five difficulty levels, they could choose one of the five to highlight.

Visualization of Progress between Snapshots

As researchers use the RML Framework tool to save data over time, they and stakeholders will want to see progress made between snapshots. This visualization could also bring to mind work they have done that is not shown in this graph, or not reflected in the framework. These insights will help improve the tool to aspects of research that it might be missing. Bullet graphs are especially helpful for seeing progress differences, which is one reason they were chosen for the visualizations in the first place. To highlight the progress, the state of the prior assessment is given at a lower saturation, and progress between snapshots shown in the regular color, as shown in Figure 12. Negative progress (when researchers thought they were further along, and later discovered more work to be done) could be shown in gray or the complementary (across the color wheel to show contrast) color.

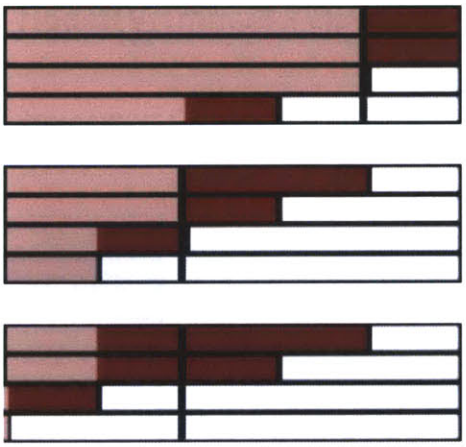

Figure 12: Proposed Visualization of Progress between Snapshots. This example is for Background Knowledge (hence the red color scheme). The change in brightness or saturation highlights the progress. This visualization does not reconcile how to show moving from one iteration to the next.

Visualization of Difficulty and Progress

When choosing how to allocate resources to advance a research project, research teams may want to zoom out from the snapshot view. Instead of looking at progress of individual milestones, they may choose to look at progress of the maturity levels as a whole compared to their perceived difficulty. Animation between this same graph for different snapshots can show survey respondents how their research has progressed over time, in a format that's easier to take in than the overall view. This visual analysis can also be considered the replacement for the lack of difficulty in the snapshot visualization. In this graph, unlike the snapshot, researchers would be able to see trends. For example, if one area is relatively easier than another (like Problem and Question formulation in the chart below), the animation between could show which areas have stalled while progress is made on other maturity levels. A proposal for this graph is shown in Figure 13 below.

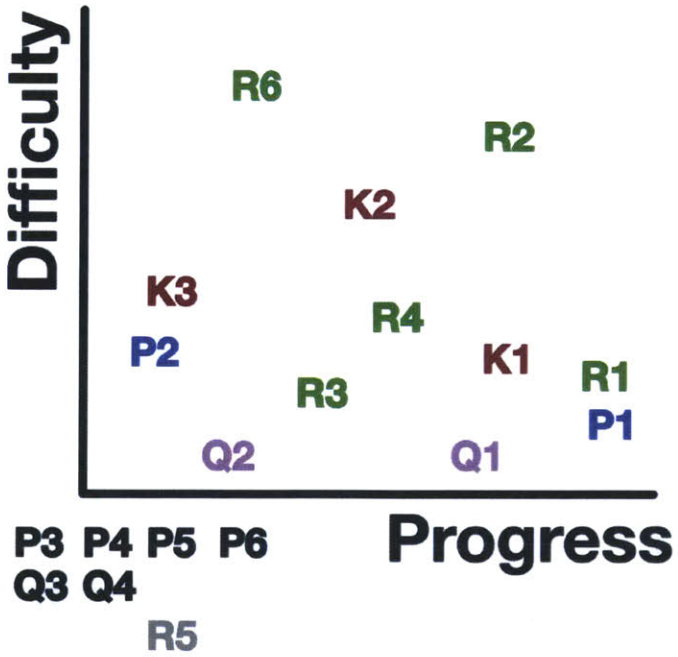

Figure 13: Visual Analysis of Difficulty and Progress. Maturity Levels that have not been started are shown in the bottom left, and not applicable levels are shown in gray, so respondents don't think they have been forgotten.

Visualization of Limitations and Risks

The limitations and risks should still appear on the overall snapshot visualization, but they merit their own page. Impediments to research are often a point of discussion among research team members and stakeholders, and seeing these challenges altogether might help people new to the project, or those with influence over these impediments, see how the impediments are affecting research. This visual analysis could also put hindrances in perspective. Those fighting low-severity impediments might decide to focus their efforts elsewhere. The details of the impediments could be given via rollover as in Figure 14. A smaller version could appear on the Snapshot Visualization, while a larger one with its own page could appear with more detail, so a printed version has a list of all impediments and their severity. Because this visualization combines nominal and ordinal data, a sorted table could also work well for it.

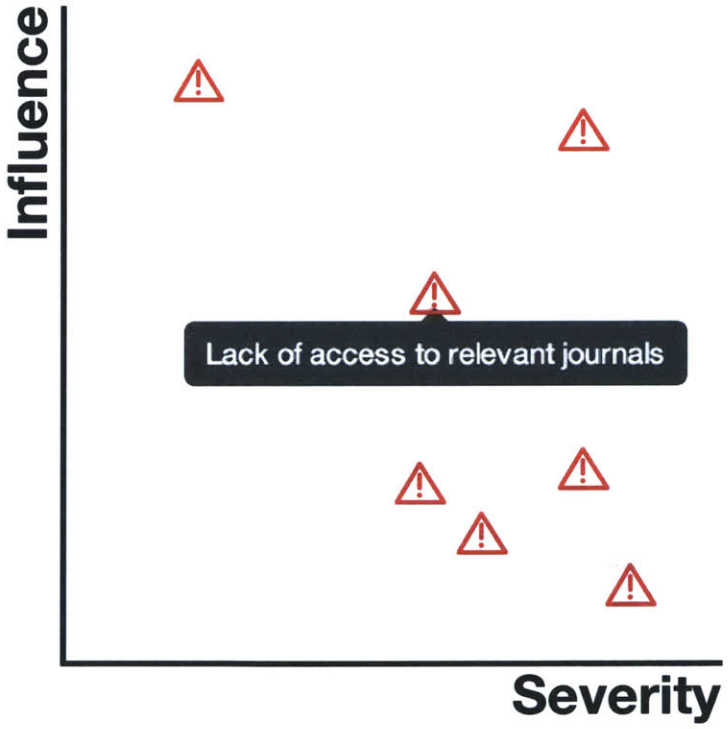

Figure 14: Proposed Visualization for smaller graph on the snapshot page. This one would have rollovers for researchers to recall these risks. Because of small size, icons could be the same.

Long Term Visualization: Research "Shape"

As this timescale and data increase, users will want to see how their projects have progressed. This visual analysis reflects the "shape" of one's research. Two hypothetical examples of this long-term visualization are shown in Figure 15 below. The top chart shows a research project in which the team first finished their Background Knowledge while determining Problem and Question Formulation. They finished procuring all Resources and finally completed their Procedure and Results (which includes dissemination). Or, projects might look like the bottom graph in which resources undulate: the team thinks they have all the resources they need, but then finds they need more, and are further behind than they realized. For Procedures and Results, the team made some progress but for whatever reason started over about halfway through the project. These visual analyses will be helpful for researchers to compare their own projects and will inform the RML research team about the shape and progress of many research projects, especially comparing different fields and time-scales.

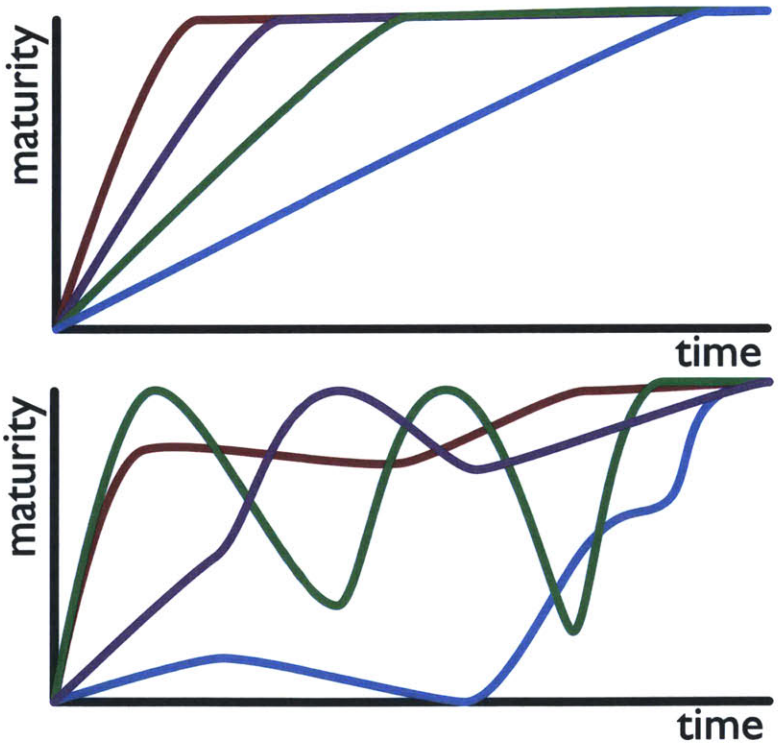

Figure 15: Hypothetical Examples of Long Term Progress Visualization (Research "Shape"). The four colors refer to the four areas of research as in Figure 7. A decrease in maturity reflects the fact that the RML Framework measures perceived progress, and researchers may find they were not as far as they had thought.

Organization of Visual Analyses

As the number of visual analyses increases, users will want to move between them easily and intuitively. The site could have a separate section for visual analyses. For each visualization, the users choose which snapshot they want to see. In the tab for Progress between Snapshots, the users choose which two snapshots to compare. Adding animations between the visual analyses, or animating the visualizations from beginning to the current snapshot would help users get different views of how their research is progressing. Adding tracking to this page will help the RML research team see which visual analyses are requested and printed the most. Examples of the tops of two such pages are shown in Figures 16 and 17

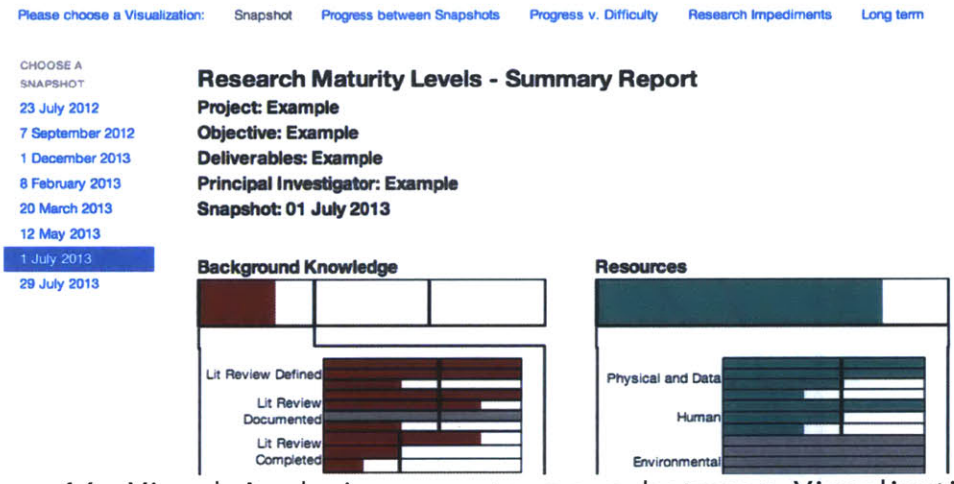

Figure 16: Visual Analysis page, to move between Visualizations and snapshots. This figure shows only the top of the page.

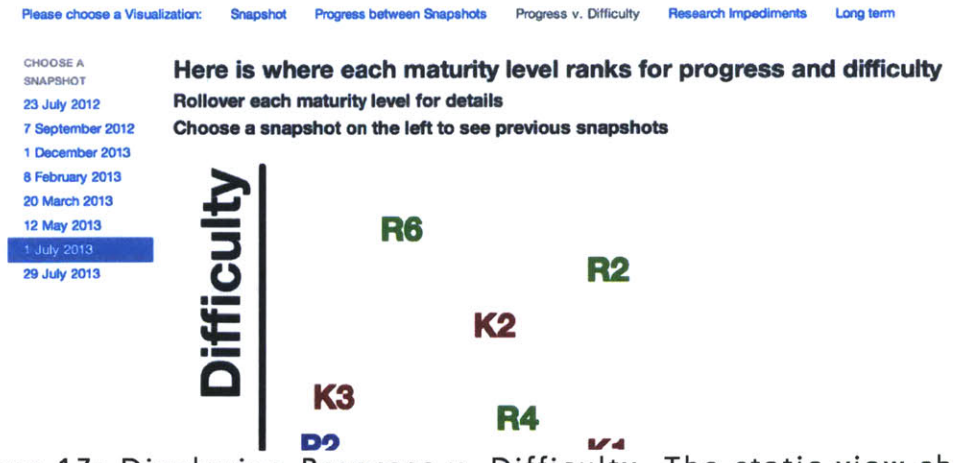

Figure 17: Displaying Progress v. Difficulty. The static view shows one snapshot, a play button could start an animation.

CONCLUSION

The Research Maturity Levels framework is designed to provide the same benefits that Technology Readiness Levels do to industry: guide a research plan, facilitate communication within and outside the research group, and allocate resources. The RML framework should also reflect the diverse nature of academic research. The online tool allows for greater dissemination and data tracking that can be used to improve the framework and the outputs that the tool provides. Better outputs increase the survey's value to researchers, and better survey design lowers the barriers to people using the survey. The more that researchers use the tool, the more data can be compiled to understand the process of academic research, which is still not understood the way that product design and development are.

Key Results and Contributions

There are two main findings for refinement of input for the survey: that difficulty ratings of levels should be done in comparison to one another, and that limitations and risks should be grouped into one category. Having the difficulty of maturity levels on an absolute scale implies that researchers understand difficulty in the same way within and between projects. In addition, researchers often want to communicate which levels are most difficult within a project and how difficult they are compared to other projects does not matter. Therefore, grouping maturity levels by larger difficulty bins is the best option. Respondents to the survey also expressed confusion between limitations and risks. As with difficulty, the data from the survey for limitations and risks should not imply more information than exists. If respondents cannot differentiate between limitations and risks, then the survey should not either. Instead, both can be categorized as 'impediments' where respondents evaluate them by how severe they are and how much control researchers have over the impediment.

The goal of all visualizations is to help researchers understand and communicate their progress. In the current tool, only a Snapshot visualization representing one point in time is available. It displays difficulty and progress data, and it is recommended that this snapshot only show one at a time, with an option to highlight levels according to difficulty. Other visualizations were proposed based on interview feedback for what researchers would want to show: progress between snapshots, the comparative difficulty and progress of maturity levels, and long term research 'shape'. Improvements were also recommended for how limitations and risks (now 'impediments') are displayed according to severity and researcher influence, and how all of these visualizations could be organized for the user's access.

Challenges and Future Work

Work remains to be done to make this site more valuable to researchers and to improve the work already done. The goal of all this work is for the framework to be a valuable model for academic research, and to gain insight into how academic research is carried out and how it can be improved.

Several aspects of the RML Framework were not investigated in this paper, including iterations, survey length, and survey wording. The idea of iterations was included in the RML Framework because academic research can be iterative: researchers know they will try several approaches. In many of the interviews conducted, respondents did not understand how to respond to the iterations section. Further interviews with academic researchers will elucidate how iterations are understood: do researchers anticipate them or recognize them only after they happen? When a better iteration model is constructed, the RML Framework can be revised to incorporate this concept and be clearer for users.

The RML Framework remains lengthy, and the questions themselves have not been investigated for clarity. The framework will benefit from an intensive investigation into which questions are more salient, which could be combined into one question, and which might be removed altogether. Conducting usability studies and tracking which clarifications are requested will also indicate which questions have confusing wording or do not make sense.

Future work can also improve upon the work in this paper. This paper recommends a change in the model for identifying limitations and risks by collapsing them into one category. The salient characteristics then become how critical the impediments are to overcome, and how much influence the researchers have over them. That model is informed by interviews with researchers and data aggregated on the tool. Further work can determine whether this model is valuable for the framework, or if hindrances to research should be input and assessed another way.

For the RML Framework to provide meaningful data on academic research, it should be tested with a representative cross-section of the academic research community. Future work can include motivating people to use the Framework and encouraging users to share it if they find it valuable.

Lastly, all visual analyses should be reviewed for graphical integrity, usefulness, and readability. Website tracking can determine which visual analyses get the most screen time and prints, and interviews with

researchers can determine how the researchers interpret these graphs, and what information they want to see when evaluating their research progress and process. Tracking and interviews should also investigate survey breakoff. Seeing incomplete surveys can show how many researchers abandon the tool and where they do so.

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APPENDICES

Appendix A: Programming References

There are many ways to implement an online survey. It is not necessary to use these resources or this implementation (Ruby on Rails). It is useful to list the resources used when developing this site as they are extensive and deserve recognition, and no web developer is an island. Others creating online surveys might also find this information helpful.

Learning the Languages, Writing the Code:

- Lynda (http://www.lynda.com) has excellent video tutorials about many different software packages and languages. It was used to learn HTML, CSS, Javascript, PHP, Ruby, Ruby on Rails.
- RailsCast (www.railscasts.com) has weekly lessons on various Ruby topics, written by Ryan Bates.
- Stack Overflow (www.stackoverflow.com) is a community of programmers with answers to almost all programming questions.
- Boston Ruby (http://bostonrb.org/) has monthly meet-ups for Ruby programmers. Problems considered insurmountable were often saved up for each month's meeting and quickly solved there with the help of more experienced programmers.

Leveraging other people's code:

- Bootstrap (http://twitter.github.io/bootstrap/) is a comprehensive CSS and Javascript package used (with minor tweaks) for site layout.
- JQuery-UI (http://jqueryui.com/) supports the progress bar interactivity and other interactive features on the site.
- Sparklines (http://omnipotent.net/jquery.sparkline/) supports the progress bar visualization; Another option is the D3 Javascript library (http://d3js.org/), which supports vector graphics.

Tools and Services used:

- Coda (http://panic.com/coda/) was used for text editing.
- Git (http://git-scm.com/) was used for version control
- The MIT Scripts Server (http://scripts.mit.edu/) hosted the first version of the site, and hosted the Ruby on Rails version for a short time.
- Heroku (www.heroku.com) hosts the site and plays very nicely with Git
- Amazon Web Services (http://aws.amazon.com) hosts some uploaded images on the site.

Appendix B: Leong Research Maturity Levels Framework

The following pages (40-56) are copied directly from Ming Leong's 2011 Thesis. This was the first revision of the Research Maturity Levels Tool. It includes a sample output from the survey.

Research Component Maturity Worksheet

Introduction:

The intent of this worksheet is to help researchers clearly identify the future goals and current states of their research activities.

Maturity levels are intended to be sequential and iterative, but allow for flexibility in process.

Project Title _____

Overall Objective _____

Tangible Deliverables _____

Research Components — Progress Summary

Resources

- ☐ Physical and Data Resources *Limitations?* ☐
- ☐ Human Resources *Limitations?* ☐
- ☐ Research Support Environment *Limitations?* ☐
- ☐ Monetary Resources *Limitations?* ☐
- ☐ Project Management *Limitations?* ☐

Background Knowledge

Iteration No. ____ of ____

- ☐ Workspace defined for literature search
- ☐ Survey of relevant literature documented
- ☐ Coherent, insightful and focused literature review completed and documented

Problem and Question Formulation

Iteration No. ____ of ____

- ☐ Broad statement of problem
- ☐ Statement of research questions
- ☐ Structured statement of problem for investigation
- ☐ Testable, concrete problem statement

Procedures and Results

Iteration No. ____ of ____

- ☐ Statement of research procedures
- ☐ Feasibility assessment completed
- ☐ Detailed research procedures fully documented
- ☐ Initial results under intended operating conditions documented
- ☐ Repeatability and validity of results documented
- ☐ Findings accepted through external review

Name _____ ☐ PI ☐ Member **Date** _____

Background Knowledge

This component begins with the identified areas as candidates for exploration. It then progresses through steps taken in a literature review and concludes with a focused and insightful review for the problem of interest.

This research component is iteration number _____ *of* _____ *anticipated final iterations.*

Explanation for current iteration:

☐ No previous iteration ☐ Pre-planned logical progression ☐ New insights obtained in prior iteration ☐ Approach of prior iteration did not work out as hoped ☐ Other reasons _____ _____

Please respond to the following prompt considering only the **current** iteration.

Maturity Level	*Not started*	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*
K1 Workspace defined for literature search	○	○	○	○	○	○	Relevant research communities identified
	○	○	○	○	○	○	Key search terms established and documented
	○	○	○	○	○	○	Citation and note-taking management system in place (eg. Endnote, summary table)
Overall	○	○	○	○	○	○	
K2 Survey of relevant literature documented	○	○	○	○	○	○	Online databases and resources searched
	○	○	○	○	○	○	Library databases searched
	○	○	○	○	○	○	Expert communities consulted
	○	○	○	○	○	○	Relevant findings summarized and archived
Overall	○	○	○	○	○	○	

Maturity Level	*Not started*	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*
K3 Focused, insightful and analytical literature review completed and documented	○	○	○	○	○	○	Similar groups of research literature identified and classified
	○	○	○	○	○	○	Information from literature synthesized and documented
	○	○	○	○	○	○	Gaps in literature and potential research opportunities identified
Overall	○	○	○	○	○	○	

Background Knowledge Limitations and Risks:

Please use the space below to articulate any limitations or risks that are impeding your ability to **develop an understanding of the background knowledge** of the project. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Background Knowledge Maturity Summary:

Each maturity level may not take the same amount of time to complete. Additionally, the effort required for each level may vary from project to project. To capture and better understand the progress of this research component, estimate the difficulty of each maturity level ranging from 10 to 100. Then, select the *one* maturity level that you feel best describes your current focus on research.

	Difficulty of maturity level										**Current level?**
K1: Workspace defined for literature search	10	20	30	40	50	60	70	80	90	100	☐
K2: Survey of relevant literature documented	10	20	30	40	50	60	70	80	90	100	☐
K3: Coherent, insightful and focused literature review completed and documented	10	20	30	40	50	60	70	80	90	100	☐

Problem and Question Formulation

This component begins with the statement of a problem of interest. It then progresses through the development of research questions, finally concludes with a testable well-defined problem statement or hypothesis with clear research expectations and scope.

This research component is iteration number _____ of _____ anticipated final iterations.

Explanation for current iteration:

☐ No previous iteration ☐ Pre-planned logical progression ☐ New insights obtained in prior iteration ☐ Approach of prior iteration did not work out as hoped ☐ Other reasons _____ _____

Please respond to the following prompts considering only the **current** iteration.

Maturity Level	*Not started*	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*
Q1 Broad statement of problem	○	○	○	○	○	○	Thorough understanding of literature and engineering context
	○	○	○	○	○	○	Identified challenges and risks
	○	○	○	○	○	○	Identified problems appropriate for research
	○	○	○	○	○	○	Impact and importance of question in broader context articulated
Overall	○	○	○	○	○	○	
Q2 Statement of research questions	○	○	○	○	○	○	Key characteristics of problem are articulated
	○	○	○	○	○	○	List of research questions related to problem
	○	○	○	○	○	○	Focused study related to preliminary questions
	○	○	○	○	○	○	Most critical question(s) selected
Overall	○	○	○	○	○	○	

Maturity Level		*Not started*	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*
Q3	Structured statement of problem for investigation	○	○	○	○	○	○	Formulate research hypothesis/ problem requirements
		○	○	○	○	○	○	Hypothesis/ problem divided into manageable subproblems
		○	○	○	○	○	○	Feasibility of addressing hypothesis/ problem determined
	Overall	○	○	○	○	○	○	
Q4	Testable, concrete problem statement	○	○	○	○	○	○	Variables (dependent, independent, controlled, intervening) identified
		○	○	○	○	○	○	Definitions and assumptions stated
		○	○	○	○	○	○	Focused research expectations and scope defined
	Overall	○	○	○	○	○	○	

Problem and Question Formulation Limitations and Risks:

Please use the list below to articulate any limitations and risks that are impeding your progress in the **formulation of research problems and questions**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Problem and Question Formulation Maturity Summary:

Each maturity level may not take the same amount of time to complete. Additionally, the effort required for each level may vary from project to project. To capture and better understand the progress of this research component, estimate the difficulty of each maturity level ranging from 10 to 100. Then, select the *one* maturity level that you feel best describes your current focus on research.

	Difficulty of maturity level										Current level?
Q1: Broad statement of problem	10	20	30	40	50	60	70	80	90	100	☐
Q2: Statement of research questions	10	20	30	40	50	60	70	80	90	100	☐
Q3: Structured statement of problem for investigation	10	20	30	40	50	60	70	80	90	100	☐
Q4: Testable, concrete problem statement	10	20	30	40	50	60	70	80	90	100	☐

Procedures and Results

This component begins with the exploration of procedures and methods to investigate research problems / hypothesis. It progresses through the development of experimental protocols for both simulation and/or physical experimentation, finally concluding with the documentation, dissemination, and acceptance of results.

Testable research question or hypothesis: _____

Description of current process: _____

These prompts consider:

☐ Mostly simulations/ theory building ☐ Mostly empirical experiments ☐ Simulations/theory building and empirical experiments equally ☐ Other _____

This research component is iteration number _____ *of* _____ *anticipated final iterations.*

Explanation for current iteration:

☐ No previous iteration ☐ **Pre-planned logical** progression ☐ **New insights** obtained in prior iteration ☐ Approach of prior iteration did not work out as hoped ☐ Other reasons _____

Please respond to the following prompts considering only the **current** iteration.

Maturity Level	*Not started*	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*	*Notes*
R1 Statement of research procedures	○	○	○	○	○	○	Options for research or prototyping procedures proposed	
	○	○	○	○	○	○	Methods and tools for proposed procedures explored	
	○	○	○	○	○	○	Appropriate and reliable procedures and tools selected	
Overall	○	○	○	○	○	○		

Maturity Level	*Not started*	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*	*Notes*
R2 Feasibility assessment	○	○	○	○	○	○	Preliminary research procedure experiments completed	
	○	○	○	○	○	○	Unexpected outcomes in research procedures detected, analyzed, and understood	
	○	○	○	○	○	○	Unexpected outcomes in research procedures interpreted	
	○	○	○	○	○	○	Core aspects of research procedures thoroughly tested in laboratory approximating operational conditions	
	○	○	○	○	○	○	Results of procedures validated to address hypothesis / problem of interest	
Overall	○	○	○	○	○	○		
R3 Detailed research procedures fully documented	○	○	○	○	○	○	Full definitions and specifications for research procedures documented	
	○	○	○	○	○	○	Practices that may affect research procedures and outcomes understood	
	○	○	○	○	○	○	Appropriate methods and/or data processing techniques selected to assess data	
	○	○	○	○	○	○	Methods for ensuring repeatability and validity of results defined	
Overall	○	○	○	○	○	○		
R4 Initial results under intended operating conditions documented	○	○	○	○	○	○	Research procedures applied to test hypothesis / problem	
	○	○	○	○	○	○	Data gathered and documented	
	○	○	○	○	○	○	Data analyzed and results understood and interpreted	
Overall	○	○	○	○	○	○		
R5 Repeatability and validity of results documented	○	○	○	○	○	○	Methods for ensuring repeatability and validity of results applied	
	○	○	○	○	○	○	Data gathered and documented using repeatable and robust procedures	
	○	○	○	○	○	○	Data analyzed and results understood using repeatable and robust procedures	
Overall	○	○	○	○	○	○		

Maturity Level		*Not started*	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*	*Notes*
R6	Findings accepted through external review	○	○	○	○	○	○	Test results shown to be consistent with hypothesis/ problem	
		○	○	○	○	○	○	Outliers and unforeseen problems explained	
		○	○	○	○	○	○	New problem statements for further exploration articulated	
		○	○	○	○	○	○	Findings formally disseminated	
	Overall	○	○	○	○	○	○		

Procedures and Results Limitations and Risks:

Please use the list below to articulate any limitations and risks that are impeding your progress in the **execution of research procedures and documentation and analysis of results**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Procedures and Results Maturity Level:

Each maturity level may not take the same amount of time to complete. Additionally, the effort required for each level may vary from project to project. To capture and better understand the progress of this research component, estimate the difficulty of each maturity level ranging from 10 to 100. Then, select the *one* maturity level that you feel best describes your current focus on research.

	Difficulty of maturity level										Current level?
R1: Statement of research procedures	10	20	30	40	50	60	70	80	90	100	☐
R2: Feasibility assessment completed	10	20	30	40	50	60	70	80	90	100	☐
R3: Detailed research procedures fully documented	10	20	30	40	50	60	70	80	90	100	☐
R4: Initial results under intended operating conditions documented	10	20	30	40	50	60	70	80	90	100	☐
R5: Repeatability and validity of results documented	10	20	30	40	50	60	70	80	90	100	☐
R6: Findings accepted through external review	10	20	30	40	50	60	70	80	90	100	☐

Resources

This component documents sub-categories of resources relevant to most research projects. Each sub-category progresses from initial planning steps to having the particular resource type fully in place.

Physical and Data Resources ☐ This resource is not relevant

This sub-category is related to tools, equipment, hardware, data sources, case studies, etc. required for research.

	Not started	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*	*Notes*
Physical and data resources operational	○	○	○	○	○	○	List of desired physical and data resources articulated	
	○	○	○	○	○	○	Sources of physical and data resources identified	
	○	○	○	○	○	○	Physical and data resources in place	
	○	○	○	○	○	○	Physical and data resources tested, de-bugged, surveyed, etc.	
Overall	○	○	○	○	○	○		

Please use the list below to articulate any limitations or risks that are impeding your ability to gather **physical and data resources**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Human Resources

☐ This resource is not relevant

This sub-category refers to students, administrators, and other human resources necessary for research.

	Not started	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*	*Notes*
Human resources operational	○	○	○	○	○	○	Research team scoped (eg. technicians, graduate students, post-docs, administrators etc)	
	○	○	○	○	○	○	Research team populated (e.g. technicians, graduate students, post-docs, administrators etc.)	
	○	○	○	○	○	○	Current research team trained and proficient in project skills	
Overall	○	○	○	○	○	○		

Please use the list below to articulate any limitations or risks that are impeding your ability to gather **human resources**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Research Support Environment

☐ This resource is not relevant

This sub-category refers to the nurturing of connections with relevant professionals to build the emotional and intellectual support environment necessary for research.

	Not started	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Notes*
Advocacy of supervisors and/or administration received	○	○	○	○	○	○	Support hiring students and staff in place
	○	○	○	○	○	○	Support streamlining purchasing in place
	○	○	○	○	○	○	Support building and maintaining lab in place
	○	○	○	○	○	○	Support to obtain money in place
	○	○	○	○	○	○	Support to operate projects in flexible, timely manner in place
Overall	○	○	○	○	○	○	
Intellectual research environment established	○	○	○	○	○	○	Relevant network of mentors and advisors identified
	○	○	○	○	○	○	Appropriate academic collaborators identified and contacted
	○	○	○	○	○	○	Relationships with relevant industry professionals established
Overall	○	○	○	○	○	○	

Please use the list below to articulate any limitations or risks that are impeding your ability to build a **research support environment**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Monetary Resources

☐ This resource is not relevant

This sub-category refers to the acquisition and availability of monetary resources necessary for research.

	Not started	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*	*Notes*
Monetary resources available for use	○	○	○	○	○	○	Funding sources identified and documented	
	○	○	○	○	○	○	Funding proposals written and submitted	
	○	○	○	○	○	○	Monetary sources in place	
Overall	○	○	○	○	○	○		

Please use the list below to articulate any limitations or risks that are impeding your ability to gather **monetary resources**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Project Management ☐ This resource is not relevant

This sub-category refers to the establishment of a system of tools to organize and manage projects related to research.

	Not started	*Less than half*	*About half completed*	*More than half*	*Almost completed/ Completed*	*Not Applicable*	*Milestones*	*Notes*
Project management resources in use	○	○	○	○	○	○	Project management resources defined (communication, content management, etc.)	
	○	○	○	○	○	○	Ethical and/or hazardous clearance issues addressed	
	○	○	○	○	○	○	Ethical and/or hazardous approval process begun	
	○	○	○	○	○	○	Clearance obtained for ethical/hazardous procedures	
Overall	○	○	○	○	○	○		

Please use the list below to articulate any limitations or risks that are impeding your ability to implement **project management** strategies. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry.

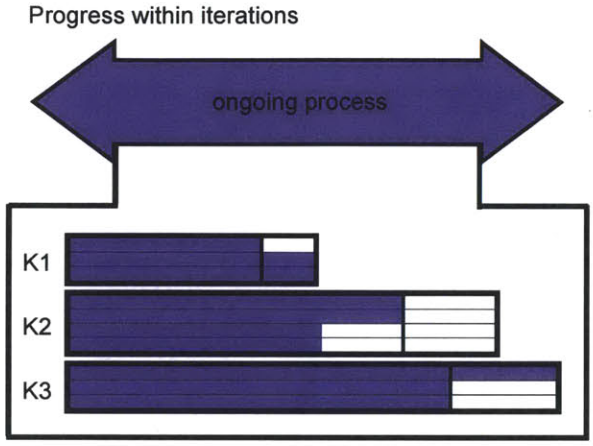
Limitation	*Mildly critical*	*Fairly critical*	*Extremely critical*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

Risk	*Low*	*Medium*	*High*
#1 _____	○	○	○
#2 _____	○	○	○
#3 _____	○	○	○

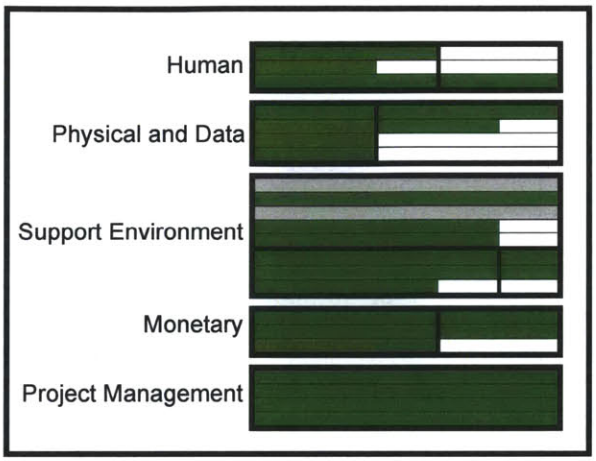
Research Maturity Levels — Summary Report

Researcher: Professor R. E. Searcher, PI
Date of Assessment: May 20, 2011
Objective: To characterize and understand the progression of academic research
Tangible Deliverables: Tool that will assess the current state of a research project; papers

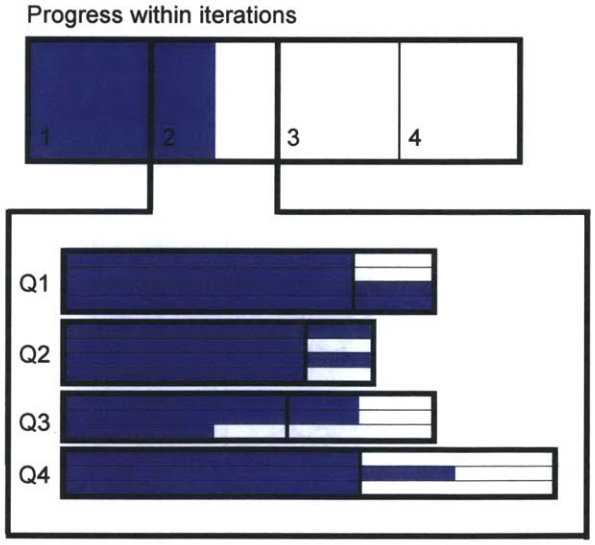
Background Knowledge



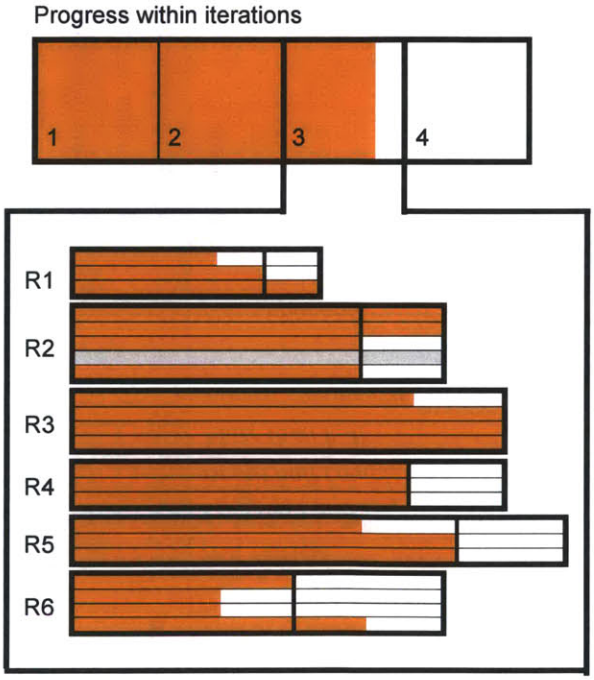
Resources



Problem and Question



Procedures and Results



Appendix C: Liggett Research Maturity Levels Framework

The following pages (58-68) are the screens in the online survey tool at rmltool.herokuapp.com as of Fall 2013. These pages represent the state of the survey at time of this publication.

Background Knowledge

This component begins with the identified areas as candidates for exploration. It then progresses through steps taken in a literature review and concludes with a focused and insightful review for the problem of interest.

Location within research iterations

This research component is number ____ of ____ total iterations.

Explanation for current iteration:

- ○ No Previous Iteration
- ○ Pre-planned logical progression
- ○ New insights obtained in previous iteration
- ○ Approach of prior iteration did not work out as hoped
- ○ Other: ____

Background Knowledge: Progress within each Maturity Level

Please respond to the following prompts considering only the **current** iteration. Pull the slider along until it expresses your current progress. In addition, each maturity level **may not take the same amount of time to complete.** To capture and better understand the progress of this research component, estimate the difficulty of each maturity level as it applies to the time necessary to complete each research component. Range is 1 to 10 (10 being hardest/longest time).

K1 Workspace defined for literature search

☐ N/A

Relevant search communities identified

☐ N/A — Not Started

Key search terms established and documented

☐ N/A — Not Started

Citation and note-taking management system in place (e.g. Endnote, summary table)

☐ N/A — Not Started

Overall

☐ N/A — Not Started

☐ N/A

Difficulty

Hardest

0

Easiest

K2 Survey of relevant literature documented

N/A

Online databases and resources searched

N/A Not Started

Library databases searched

N/A Not Started

Expert communities consulted

N/A Not Started

Relevant findings summarized and archived

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

K3 Focused, insightful and analytical literature review completed and documented

N/A

Similar groups of research literature identified and classified

N/A Not Started

Information from literature synthesized and documented

N/A Not Started

Gaps in literature and potential research opportunities identified

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

Background Knowledge Limitations and Risks

Please use the list below to articulate any limitations and risks that are impeding your **progress in developing and understanding the background knowledge of the project**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry. *If you feel that there are no limits or risks for this category, please leave these fields blank.*

Limitations **Level**

+Add Limit

Risks **Level**

+ Add Risk

Submit

Problem and Question Formulation

This component begins with the statement of a problem of interest. It then progresses through the development of research questions, and finally concludes with a testable well-defined problem statement or hypothesis with clear research expectations and scope.

Location within research iterations

This research component is number of total iterations.

Explanation for current iteration:

- No Previous Iteration
- Pre-planned logical progression
- New insights obtained in previous iteration
- Approach of prior iteration did not work out as hoped
- Other:

Problem and Question Formulation: Progress within each Maturity Level

Please respond to the following prompts considering only the **current** iteration. Pull the slider along until it expresses your current progress. In addition, each maturity level **may not take the same amount of time to complete**. To capture and better understand the progress of this research component, estimate the difficulty of each maturity level as it applies to the time necessary to complete each research component. Range is 1 to 10 (10 being hardest/longest time).

Q1 Broad statement of Problem

N/A

Thorough understanding of literature and engineering context

N/A — Not Started

Identified challenges and risks

N/A — Not Started

Identified problems appropriate for research

N/A — Not Started

Impact and importance of question in broader context articulated

N/A — Not Started

Overall

N/A — Not Started

N/A

Difficulty

Hardest

0

Easiest

Q2 Statement of research questions

N/A

Key characteristics of problem are articulated

N/A Not Started

List of research questions related to problem

N/A Not Started

Focused study related to problem

N/A Not Started

Most critical question(s) selected

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

Q3 Structured statement of problem for investigation

N/A

Formulate research hypothesis/problem requirements

N/A Not Started

Hypothesis/problem divided into manageable subproblems

N/A Not Started

Feasibility of addressing hypothesis/problem determined

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

Q4 Testable, concrete problem statement

N/A

Variables identified (dependent, independent, controlled, intervening

N/A Not Started

Definitions and assumptions stated

N/A Not Started

Focused research expectations and scope determined

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

Q4 **Testable, concrete problem statement**

N/A

Variables identified (dependent, independent, controlled, intervening

Not Started

N/A

Definitions and assumptions stated

Not Started

N/A

Focused research expectations and scope determined

Not Started

N/A

Overall

Not Started

N/A

Difficulty

Hardest

0

Easiest

Problem and Question Formulation Limitations and Risks

Please use the list below to articulate any limitations and risks that are impeding your **progress in the formulation of research problems and questions**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry. *If you feel that there are no limits or risks for this category, please leave these fields blank.*

Limitations **Level**

+Add Limit

Risks **Level**

+ Add Risk

Submit

Liggett Framework | 15 October 2013

Lock Snapshot

Background Knowledge | Problem and Question Formulation | Procedures and Results | Resources | View Snapshot Progress

Procedures and Results

This component begins with the exploration of procedures and methods to investigate research problems and hypothesis. It progresses through the development of experimental protocols for both simulation and/or physical experimentation, finally concluding with the documentation, dissemination, and acceptance of results.

Location within research iterations

This research component is number _____ of _____ total iterations.

Explanation for current iteration:

- No Previous Iteration
- Pre-planned logical progression
- New insights obtained in previous iteration
- Approach of prior iteration did not work out as hoped
- Other:

Please explain your process

Testable research question or hypothesis:

Description of current process:

These prompts consider...

- Mostly simulations/theory building
- Mostly empirical experiments
- Simulations/theory building and empirical experiments equally
- Other:

Procedures and Results: Progress within each Maturity Level

Please respond to the following prompts considering only the **current** iteration. Pull the slider along until it expresses your current progress. In addition, each maturity level **may not take the same amount of time to complete**. To capture and better understand the progress of this research component, estimate the difficulty of each maturity level as it applies to the time necessary to complete each research component. Range is 1 to 10 (10 being hardest/longest time).

P1 Statement of research procedures

N/A

Options for research or prototyping procedures proposed

N/A — Not Started

Methods and tools for proposed procedures explored

N/A — Not Started

Appropriate and reliable procedures and tools selected

N/A — Not Started

Overall

N/A — Not Started

N/A

Difficulty

Hardest

0

Easiest

P2 Feasibility assessment

N/A

Preliminary research procedure experiments completed

N/A — Not Started

Unexpected outcomes in research procedures detected, analyzed, and understood

N/A — Not Started

Unexpected outcomes in research procedures interpreted

N/A — Not Started

Core aspects of research procedures thoroughly tested in laboratory approximating operational conditions

N/A — Not Started

Results of procedures validated to address hypothesis/problem of interest

N/A — Not Started

Overall

N/A — Not Started

N/A

Difficulty

Hardest

0

Easiest

P3 Detailed research procedures fully documented

N/A

Full definitions and specifications for research procedures documented

N/A Not Started

Practices that may affect research procedures and outcomes understood

N/A Not Started

Appropriate methods and/or data processing techniques selected to assess data

N/A Not Started

Methods for ensuring repeatability and validity of results defined

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

P4 Initial results under intended operating conditions documented

N/A

Research procedures applied to test hypothesis/problem

N/A Not Started

Data gathered and documented

N/A Not Started

Data analyzed and results understood

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

P5 Repeatability and validity of results documented

N/A

Methods for ensuring repeatability and validity of results applied

N/A Not Started

Data gathered and documented using repeatable and robust procedures

N/A Not Started

Data analyzed and results understood using repeatable and robust procedures

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

P6 **Findings accepted through external review**

Test results shown to be consistent with hypothesis/problem

N/A Not Started

Outliers and unforeseen problems explained

N/A Not Started

New problem statements for further explanation articulated

N/A Not Started

Findings formally disseminated

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

Procedures and Results Limitations and Risks

Please use the list below to articulate any limitations and risks that are impeding your **progress in the execution of research procedures and documentation and analysis of results**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry. *If you feel that there are no limits or risks for this category, please leave these fields blank.*

Limitations **Level**

+Add Limit

Risks **Level**

+ Add Risk

Submit

Lock Snapshot

Liggett Framework | 15 October 2013

Background Knowledge | Problem and Question Formulation | Procedures and Results | Resources | View Snapshot Progress

Resources

This component documents sub-categories of resources relevant to most research projects. Each sub-category progresses from initial planning steps to having the particular resources type fully in place.

Location within research iterations

This research component is number of total iterations.

Explanation for current iteration:

- No Previous Iteration
- Pre-planned logical progression
- New insights obtained in previous iteration
- Approach of prior iteration did not work out as hoped
- Other:

R1 Physical Data and resources operational

N/A

List of desired physical and data resources articulated

N/A Not Started

Sources of physical and data resources articulated

N/A Not Started

Physical and data resources in place

N/A Not Started

Physical and data resources tested, de-bugged, and surveyed

N/A Not Started

Overall

N/A Not Started

Difficulty

Hardest

0

Easiest

R2 Human resources operational

N/A

Research team scoped (e.g. technicians, graduate students, post-docs, administrators, etc.

N/A Not Started

Research team populated (e.g. technicians, graduate students, post-docs, administrators, etc.

N/A Not Started

Current research team trained and proficient in project skills

N/A Not Started

Overall

N/A Not Started

Difficulty

Hardest

0

Easiest

R3 Advocacy of supervisors and/or administration received

N/A

Support for hiring students and staff in place

N/A Not Started

Support for steamlining purchase in place

N/A Not Started

Support for building and maintaining lab space in place

N/A Not Started

Support to obtain money in place

N/A Not Started

Support to operate projects in flexible, time-friendly manner in place

N/A Not Started

Overall

N/A Not Started

Difficulty

Hardest

0

Easiest

R4 Intellectual research environment established

N/A

Relevant network of mentors and advisors identified

N/A Not Started

Appropriate academic collaborators identified and contacted

N/A Not Started

Relationships with relevant industry professionals established

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

R5 Monetary resources available for use

N/A

Funding sources identified and documented

N/A Not Started

Funding proposals written and submitted

N/A Not Started

Monetary sources in place

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

R6 Project management resources in use

N/A

Project management resources defined (communication, content management, etc.)

N/A Not Started

Ethical and/or hazardous clearance issues addressed

N/A Not Started

Ethical and/or hazardous approval process begun

N/A Not Started

Clearance obtained for ethical/hazardous procedures

N/A Not Started

Overall

N/A Not Started

N/A

Difficulty

Hardest

0

Easiest

Resources Limitations and Risks

Please use the list below to articulate any limitations and risks that are impeding your **ability to aquire these resources**. Then use the scale to indicate the criticality of overcoming the limitation and/or the level of risk for each entry. *If you feel that there are no limits or risks for this category, please leave these fields blank.*

Limitations	**Level**
+Add Limit	

Risks	**Level**
+ Add Risk	

Submit