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Metafora: A Web-based Platform for Learning to Learn Together in Science and Mathematics

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Abstract— This paper presents Metafora, both a platform for integrated tools as well as an emerging pedagogy for supporting *Learning to Learn Together* in science and mathematics education. Our goal is to design technology that brings education to a higher level; a level where students not only learn subject matter, but also gain a set of critical skills needed to engage in and self-regulate collaborative learning experiences in science and math education. To achieve this goal, we need to understand how educational technology can bring students' attention to, and promote these higher-level skills. We first discuss the core skills that students need as they learn to learn together. We then present a platform and pedagogy to support the acquisition of the critical skills. Finally, we present an example use of our system based on results from pilot studies. This example demonstrates interaction with the platform to highlight potential benefits and limitations of our approach to promoting the associated skills.

Index Terms—N.1.II Learning via Discovery, N.1.V Educational Simulations, N.3.I Social Learning Techniques, N.3.II Collaborative Learning Tools, N.3.IV Knowledge Sharing, N.3.V Peer Tutoring N.5.II Learning Objects

1 Introduction

This paper presents a type of pedagogy and supporting educational technology intended to promote secondary education students' explicit articulation and reflection on group work. Students are enabled and encouraged to regulate their own group learning via planning, discussion, and reflection, as they undertake complex challenges in science and mathematics.

Research and development of educational software in the field of Technology-Enhanced Learning (TEL) in general and in Computer-Supported Collaborative learning (CSCL) in particular, have attended to individual meta-learning (e.g. [1]) and separately to scaffolding the inquiry process and encouraging student collaborations. In particular, several tools have been developed to support both inquiry and constructionist learning by offering access to simulators and encouraging students to explore phenomena (see [2], [3] for reviews). Moreover, specific attention has been given to the process of inquiry itself by, for example, suggesting specific steps that can be undertaken and prompts to scaffold students (for examples see the Web-based Inquiry Science Environment [4], Rashi [5], or nQuire [6]). Research has demonstrated the potential of such tools in improving both learning and students' motivation to learn (e.g. [7], [8]). Moreover, research on enabling and scaffolding group-work has demonstrated that carefully designed tools (such as the Virtual Mathematics Teams [9]) can transform learning from an individual process to a process where students can support each other's intellectual engagement by sharing knowledge, learning through interaction and co-construction of knowledge [10], [11].

However, there has been little attention on "Learning to Learn Together" (L2L2), i.e. supporting students to focus on the meta-level of how they learn with and from each other as they work in groups to solve challenging problems. With this work, we seek to answer the question: *How should educational technology be designed in order to bring students' attention to, and promote learning to learn together*? We offer a system designed to bring students' attention to and improve these higher-level, collaborative learning skills, while they engage in complex domain learning activities.

While recognizing the importance of the standard skills promoted by more traditional systems, our work is motivated by the importance of moving beyond domain-specific skills and focusing on the collaborative competencies associated with group learning that today's complex, fast-paced environment demands [12]. We seek to achieve this objective through design-based research (DBR) to design a platform that not only allows students to engage in and learn these skills, but actually encourages them to do so.

This research is conducted in the context of the Metafora project[1] that takes its name from its focus on 'social meta-learning' and in particular on the recognition the support of collective reflection on and improvement of social learning in 'forums', hence 'meta-fora'. Accordingly, the pedagogy and software platform are unique in that

[1] http://www.metafora-project.org

they focus, support, and make explicit the development of L2L2 skills as students engage in domain-specific activities. The suite of tools offered within the platform range from typical exploratory learning environments to a tool that is developed specifically to allow students to explicate and reflect their group learning process. The types of software tools currently included are:

- *Planning / Reflection Tool:* provides a visual language to support students in planning and reflecting; activities, roles, resources, task assignments and attitudes are visualized, discussed, and reflected upon.
- *Discussion Tools:* provide space for students to create both in-the-moment chat, and structured, graphical discussions and argumentation.
- *Domain Tools / Microworlds*: present simulations and exploration spaces to students, where they can tackle interesting challenges and gain understanding of the underlying scientific or mathematical models.

In the following section, we describe Metafora's pedagogy and how it supports L2L2 in more detail. We then explain how these skills are supported and encouraged by our software platform, and offer an example of their use. In particular, we focus on how the tight integration of these tools in one platform provides opportunities for collaborative learning behaviors to emerge and (in combination with the pedagogy) the possibility to encourage students to reflect on and (if necessary) improve their L2L2 process. We close by offering conclusions about the strengths and limitations of the current version of the system, and describe future work we are planning to both exploit the strengths and alleviate the current weaknesses of the framework.

2 The Pedagogy: Learning to Learn Together

Learning To Learn Together is not a uniform, easily dissected process, but rather a complex set of competencies. L2L2 unites a number of skills that must be understood not in isolation, but in relation to and interaction with one another. We now consider some subcomponents of the L2L2 process and how they are interlinked.

One key, high-level component of L2L2 is being aware of the distribution of leadership within a group and how this changes as the group works on the task – what is often referred to as *distributed leadership*. Moving away from traditional static scenarios, where a single leader (typically the teacher) controls the flow of work, we take the view that in effective groups, leadership is distributed, each member is willing to take responsibility for regulating their group learning with a collective orientation. Prior research has shown that a diversity of expertise and interests can be externalized through leadership moves in different tasks and contexts [13], [14], [15]. To make leadership moves, members need to negotiate and develop a collective understanding of both their progress on their task and how their team is working together.

A second high-level component competency of L2L2 is *mutual engagement* via joint attention to shared artifacts. In order for a group to be successful, the members must engage with one another on more than a surface level. They need to share deeper concepts, plans, and engage in collaborative meaning making. Mutual engagement manifests through collaborative spaces, where group members can work together synchronously and asynchronously. Also crucial to mutual engagement is an integrated workspace, allowing students to move freely between varied tools that serve different purposes, but also allowing them to easily share artifacts and concepts developed in other spaces without losing context.

Related to mutual engagement but worth discussing separately is a third competency of L2L2: *help seeking and giving* [16], [17]. Newman [18] (based on Nelson-LeGall's work [16]) defines a general model of help-seeking that highlights the importance of several metacognitive skills related to help-seeking, starting from the need to be aware of task difficulty, the necessity of asking for help when the way forward is not clear, and evaluating the cost and benefit of a help request. Affective characteristics also come into play particularly because help seeking is regarded as a social transaction that takes place within an interpersonal relationship [19]. Particularly in classroom settings there are various reasons for avoiding seeking help; yet it is important for students to identify their own help seeking and giving processes. Students should move towards requesting help that aims to generally demonstrate or explain the method by which the problem can be solved. Appropriate help giving allows the student to retain responsibility for the solution and acquire new knowledge. This way the help seeker not only remedies her immediate problem, but also ensures long-term autonomy.

Finally, the fourth key component of L2L2 that we will distinguish is *reflection on the group learning process*. In order to work on the meta-cognitive level, students must not only engage in planning, experimentation, discussion, etc., they must also reflect on their use of these processes. They must consider *how* they have been learning together, looking back to analyze their learning activities and their group dynamics. Through this reflection, the students should be able to identify what worked and what did not work in their group learning process.

These four components are clearly important aspects of the holistic process we term L2L2. However, to understand the process of learning to learn together, we must consider these competencies as they intertwine and overlap with one another when students are faced with particular challenges in a certain context. While the Metafora platform is designed to allow students to engage in a variety of activities (including real-world activities that require planning and discussion stages) it is particularly geared towards constructionist contexts with microworlds or simulations.

Accordingly, the Metafora pedagogy relies on posing open-ended, ill-structured challenges to students (c.f. [20]) and takes into account that constructionism suggests that learning is enriched in an environment where students generate meanings as a result of collective construction of and experimentation with models, c.f. [21] and for a recent review [3]. Attention is drawn to the meaning that students generate rather than to the extent to which they understand the products of mathematics and science in their abstract form. We purposefully used the word 'collective' to denote that, in contrast to some critics (see e.g. [22]), constructionism studies embrace the social aspect of meaning generation and look deeply into the process of argumentation and discussion over meanings during constructionist activity (c.f. [23] where also the notion of 'distributed constructionism' is elaborated with three activity categories of *discussing*, *sharing* and *collaborating* on constructions). In this context of collective constructionist learning with models, a challenge refers to a complex open problem situation relating to a real or realistic phenomenon within a socially relevant situation.

The Metafora challenges encourage the development of an understanding of the scientific nature and complexity of phenomena by providing access to constructionist environments. In these environments, students generate meaning by tinkering with the rules with which digital models operate, questioning their behaviors and thinking about the phenomena they simulate [3], [24].

Of course, as mentioned section 1, inquiry learning in science, in which students explore a physical phenomenon with simulation software and later are presented with underlying scientific concepts and measurements to tie back to their experience, is not a new endeavor [2], [7]. Similarly, in mathematics, purposefully designed microworlds have been shown to allow students to explore abstract concepts by making objects accessible in the environment and allowing the exploration of the mathematical relationships between and within the objects, as well as the representations that make them accessible [3], [24], [25]. Learning through experimentation and simulation, using models of physical phenomena with a means to scientifically measure and check results, provides students with a direct experience of phenomena, while at the same time allowing them to crosscheck that experience with scientific principles. Students are able to experiment with various aspects of models, e.g. controlling time, interconnecting representations, and measuring various aspects of a phenomenon in sync with its evolution.

Supporting this constructionist and inquiry-related activity and at the same time draw attention to the higher level learning skills introduces additional requirements for both the platform and the pedagogy. The supporting technology should encourage students to go beyond understanding just the rules, properties and relations underlying the microworld models, to also change or re-create models of their own, and then share, discuss and argue about their findings with their group or other groups. This process of group meaning generation requires skills from across the different aspects of L2L2: organizing, discussing, seeking and offering help from peers when needed. A successful, computer-based L2L2 platform will provide a space and a suite of tools that both encourage and allow practice of these competencies. We present in the next section how Metafora is designed to provide this space.

3 *Metafora - A Platform to Support L2L2*

In order to describe how a system can support the various aspects of L2L2 outlined in section 2, we now present our software platform. We argue that these L2L2 skills cannot be supported by simple, isolated tools, and thus our platform integrates a variety of complex learning tools and provides a general framework to allow integration of further tools. First, we describe the Planning/Reflection Tool, which is the central area for students to plan, organize, and reflect on their group learning process. We then describe the discussion tools that allow various methods of communication between students as they work. Finally, we offer some detail of the types of challenges and domain tools offered in Metafora, and describe the overall technical architecture that allows for these tools to be integrated into one platform. Throughout these descriptions we highlight the specific manner in which these tools, and their integration, enable and promote the skills necessary for successful L2L2.

The Planning / Reflection Tool

This tool is central both in a practical sense and in a pedagogical sense. From a practical perspective, it plays a prominent role as an entry point and a pivot to the other tools. From a pedagogical perspective, it is designed with the L2L2 process in mind. First, it directly supports *distributed leadership* by allowing any group member to create plans, organize the group work, and assign tasks and roles. Planning elements are represented as "cards" which comprise a visual language representing activity stages, processes, resources, attitudes, and roles. Students arrange and connect these cards in a planning map to explicitly represent the work they have done and the tasks they are completing, or are planning to do (see Fig. 1 for an example). The tool fosters *mutual engagement* by providing this collaborative space that is easily used in different student configurations (several students sitting at the same computer as a group, or remote collaboration, e.g. the internet from home). Lastly, it supports *reflection on the group learning process*, as the planning map itself serves as an impetus for reflection both with respect to the progress of activities (marking cards as started, finished) and the fulfillment of the planned activities (i.e. comparing planned activities with preformed activities). Additionally, the tool promotes *joint attention to shared artifacts* by allowing students to enter tools and domain workspaces directly.

The Planning/Reflection Tool provides this functionality as a web-based application offering a visual language for planning, enacting, and reflecting on Metafora learning activities. Even though it is built as a stand-alone web application, it unfolds its full potential embedded within the Metafora platform and connected to the other learning tools. Students create plans for facing a challenge / conducting inquiry, and directly enter tools from this plan, using an automatic login to the other tools and providing the work context needed to tackle specific tasks within the challenge. This plan can be considered a living artifact that is continuously being revised, checked and reflected upon.

Technically, the Planning/Reflection Tool uses the Google Web Toolkit for the graphical user components and client-server communication to transmit user actions performed in a web browser. Since it allows collaborative usage remotely, actions being performed by one user are propagated actively to all the peer students working in the same context/group. To enact this, server push technology is used to overcome the limitations of the conventional request-response protocol of web-based applications. The Planning/Reflection tool also interacts with other components of the Metafora system to allow seamless transition and semantic references from and into learning tools. This inter-tool communication uses the loosely coupled XMPP-based architecture as described in the later section "*The Metafora Platform*".

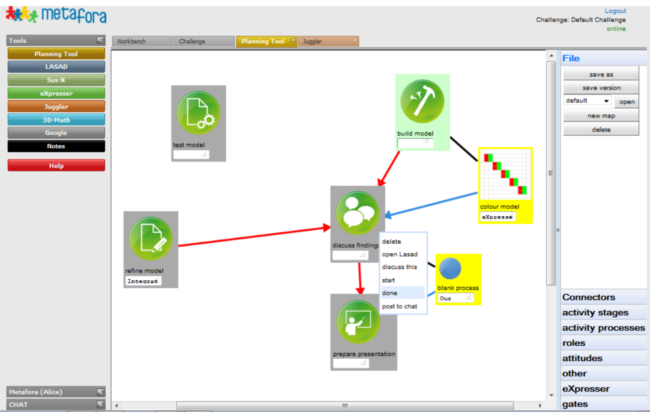

Fig. 1. Plan used as a graphical organizer. Started activities are marked yellow, finished activities in green.

Discussion Tools

Metafora provides discussion tools to allow general communication and collaboration for teams, but also aimed specifically to support the L2L2 process. One crucial enhancement of Metafora discussion spaces is ability to include snapshots and links to artifacts from the different tools, which we refer to as "referable objects". These referable objects are shared to discussion spaces from other tools and can be viewed (text or thumbnail images) as components of the discussion, but can also be accessed in the context of the original creator tool through return links (Fig. 2). This integration offers the key requirements of *mutual engagement*, allowing students to bring individual work into a collaborative space. This behavior also offers the ability for students to *seek and offer help* to one another, allowing them to share individual artifacts to exemplify problems or concepts that need to be mutually understood to offer support to one another. Finally, this ability offers opportunity for *reflection*, on both learning activities (giving students a space to compare and discuss the artifacts they have created) and on group dynamics (giving students a space to discuss their overall workflow, balance of contributions, etc.).

Two types of discussion spaces serve different purposes in Metafora. First, the chat tool offers a quick and ever-present space for students to gain each other's attention and share informal thoughts in situ as they are working with any of the Metafora tools. By allowing the use of referable objects, the students can use references to planning cards or microworld objects without the need of anaphoric or deictic language that would disrupt their communication. This need emerged from early experimentation with the system and is supported by related research e.g. [26].

Second, the LASAD[2] tool (**L**earning to **A**rgue: Generalized **S**upport **A**cross **D**omains) [27] offers a more structured approach to discussion through argumentation graphs (see Fig. 2). These types of argumentation graphs have been shown to support collaborative learning through improvement in discussion and argumentation skills [28]. To customize the tool for a specific use, authors (teachers and researchers) can create new templates, where sets of box types and links are defined to specify the types of argumentation elements students will use within their argument diagrams.

Specific templates are defined and continually refined to configure LASAD specifically for the L2L2 process. These box elements are designed to urge students toward productive discussions of microworld phenomena. We have developed one such template based on constructionist ideas that provides specialized boxes to help students focus on the key aspects of L2L2 during their microworld exploration.

For example, Fig. 2 shows two specific boxes from the constructionist template. The first is a *Help Request*, giving students the space to ask for help regarding specific microworld artifacts, and prompting them to explain the issue they are having. In this case, a student asks for help about a model in eXpresser, which is designed to support learning of algebra through the identification of algebraic rules for figural patterns (see [29], [30] for more details). Another student responds by offering a *Microworld action*

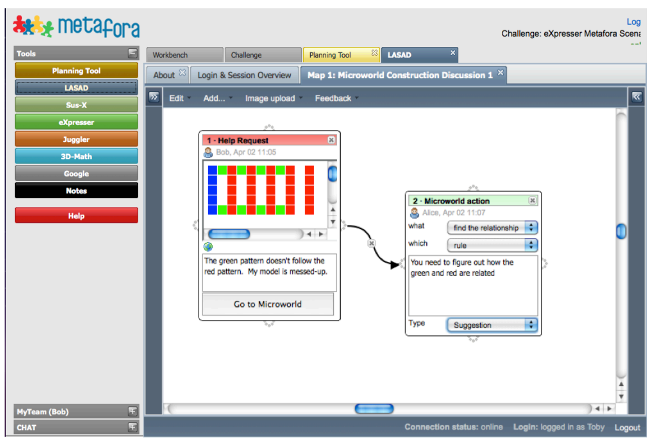

Fig. 2. LASAD map using the Constructionist template. A referable object is used within a *Help Request* box (left) that links to an eXpresser workspace with the model shown in the thumbnail image. Any user can interact with this eXpresser workspace by clicking the "Go To Microworld" button. The constructionist template also offers other focused box types, like the *Microworld action* box (right).

[2] http://cscwlab.in.tu-clausthal.de/lasad

as a suggestion. This box allows the user to choose from drop-down list to specify the type of action and the part of the microworld referenced. In the given example, the helping student specifies that the other needs to *find a relationship*. Other types of available microworld actions are: *change, observe, define, crosscheck, repeat, and reproduce behavior*.

Through this template, students are able to *seek help from and offer help to one another* [30]. The specific box types and drop down menus also help students focus their discussions on the key concepts involved in constructionism. Through repeated use, students become accustomed to the types of contributions that should be considered when analyzing and responding to discussion items.

To promote the more complex aspects of *mutual engagement*, Metafora and LASAD are integrated on a deep level, allowing the students to share and discuss artifacts (such as models from microworlds or activity stages from the planning tool). This integration comes in the form of two major technical enhancements. The first is the ability for LASAD to display URL elements within an argument box (see image contained in left box in Fig. 2). This allows LASAD to display thumbnail images representing a shared object, so that the object itself can be seen inside the LASAD argument map. The second technical enhancement is to allow the outside tools (including the Metafora framework) to create boxes inside of LASAD argument graphs, effectively allowing the users of other tools inside Metafora to create referable objects inside of LASAD. These other tools issue xml commands over the command channel (see Fig. 4). The system can also allow users to view and inspect these objects in their native environment through the "Go to Microworld" button in the LASAD box (Fig. 2).

Challenges / Microworlds

As described in Section 2, specific challenges invite opportunities to engage in L2L2, and integrated microworlds and simulators allow students to further explicate their process of learning together. Metafora includes many challenges involving five current microworlds for science and mathematics. For a specific example, we consider a challenge in the context of the 3D Juggler microworld (Fig. 3). Students are given the challenge to collectively design a three dimensional Juggler game based on the available simulation by creating the technical and functional specifications for the game [31]. They can use the simulation to experiment and gain understanding of the underlying concepts so that they can be accurate in their designs. The simulator intentionally contains a relatively large number of variables (eight for each of the balls), and a dynamic manipulator for the position of the launch pads. Students also control the 'camera' for perusal of the phenomenon from all angles. Some of the variables such as azimuth are not typically found in science curricula so students need to actively discover their underlying meaning. The phenomenon offered for experimentation within this microworld embodies several classic concepts, such as the need for two angular measures to define the trajectory of a ball (height and azimuth), the instant nature of the force producing a continually changing velocity due to gravity, and the irrelevance of mass when there is lack of friction. Research has shown that students have deeply engrained misconceptions about such concepts, partly formed through their experiences with the physical world [32].

The Metafora Platform

All of the different tools are brought together in the Metafora platform to allow students to engage in L2L2 as they work on challenges like the one described above.

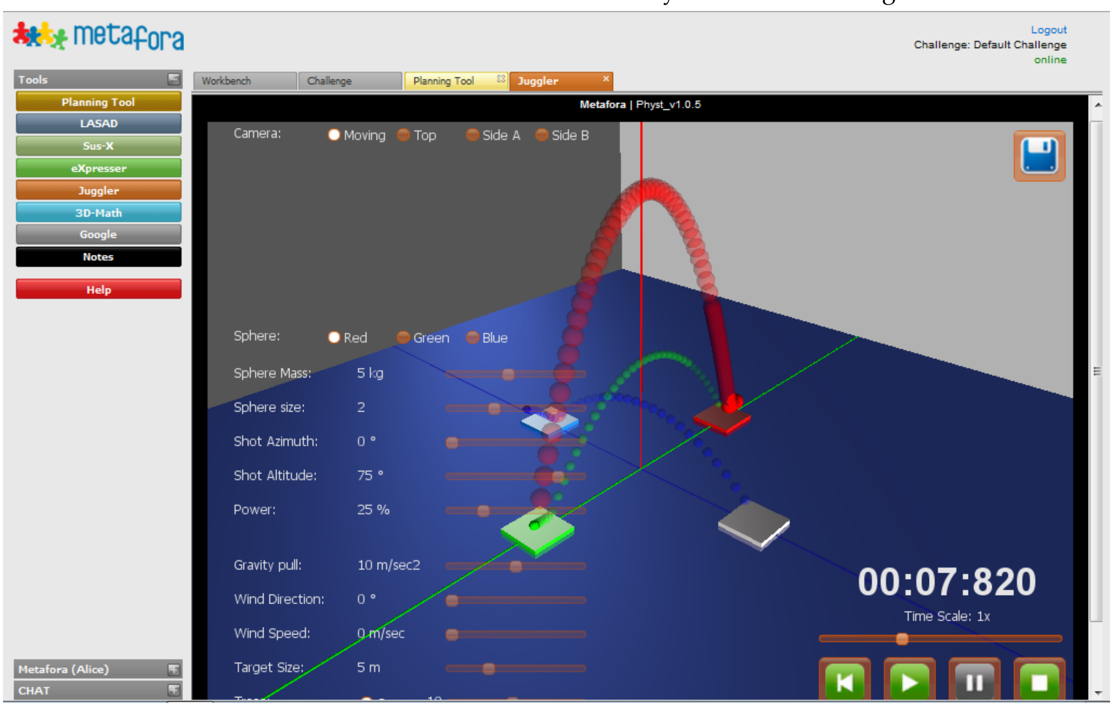

Fig. 3. Screenshot of the Metafora platform with several learning tools opened; the current focus is on the Juggler physics microworld, while the Planning Tool is also opened (see tabs on the upper border).

The Metafora platform serves both as a toolbox for these tools and also as communication architecture to support cross-tool interoperability. The toolbox facet of the system provides a graphical container framework in which the diverse learning tools can be launched and used. Fig. 3 gives an impression of the Metafora system with the platform parts on the top and left borders and the graphically integrated tools in the main panel from center to right.

Basic globally-available functionalities are user management (login / logout, and group membership for both local groups of students sitting at one computer as well as remote, collaborative groups), a chat system to discuss and organize work between group members, and a global help request function that allows a member of the team to notify the rest of the team of a particular issue and bring their attention to the same tool.

To establish the integration of tools and the unified platform, cross-tool interaction is mediated by a flexible communication architecture based on the XMPP protocol (Extensible Messaging and Presence Protocol). All the tools can subscribe and publish to dedicated XMPP channels (see Fig. 4). One channel is reserved for inter-tool commands, issued by tools or the platform. These commands include prompting a user to navigate between tools or allowing a user to send references to artifacts from one tool to another (what we termed “referable objects” in the *Discussion Tools* sub-section).

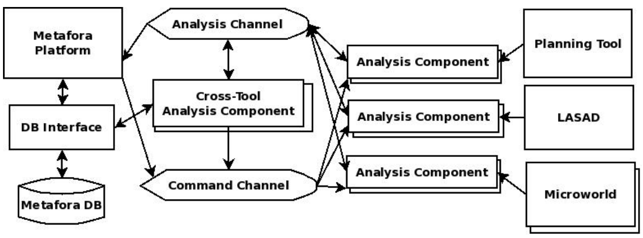

Fig. 4. Communication Diagram for the Metafora platform, showing the message flow of the architecture that allows for both analysis and control between the loosely coupled tools comprising the system.

This XMPP communication architecture is also used for the analytical system that is currently under development. A second communication channel, the analysis channel (see Fig. 4), is used by components that can perform automated analyses ranging from low-level activity indicators (such as indicating the creation or modification of artifacts) to high-level analyses (such as identification of whether a student is deemed to be “struggling” within a tool). A cross-tool analysis agent can then monitor this channel, and offer higher-level analysis of student work that the project team is still in the process of defining based on experimentation [30]. Finally, filtered views of this analysis channel can be displayed to students, teachers, and researchers to provide insight into the L2L2 process, for individuals and teams as a whole.

4 Demonstrating Metafora in Action

In sections 2 and 3, we presented the concept of L2L2 and the component tools of Metafora. However this offers only a partial understanding of the nature of the Metafora system. The complexity of interaction when considering multiple students using the multiple tools and demonstrating multiple L2L2 competencies all combine to create a complex situation to consider. In Fig. 5, we present a mapping of the main L2L2 competencies on which we focus, and some of the prominent relationships between these competencies and the given tools. As this is a static figure it cannot offer a complete picture of all the interleaving relationships between skills and tools, but attempts to provide a broad conceptual mapping and an example of the complexity of the both theory of L2L2 and the Metafora platform designed to support it.

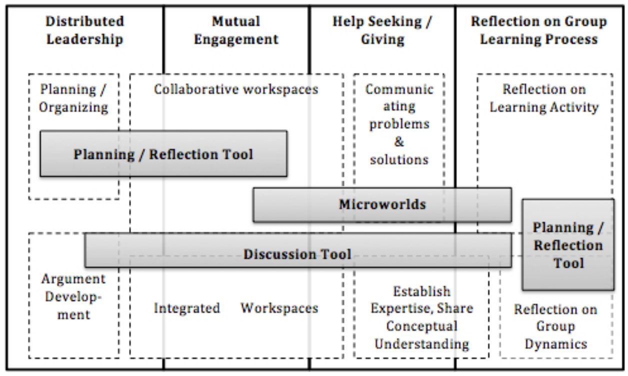

Fig. 5. The breakdown of supported L2L2 skills and their relationship with the Metafora tools. The L2L2 skills are illustrated beneath the Metafora software components that support those skills. From top to bottom, we can see, generally, how students move through use of the tools; starting with planning, then engaging in microworlds, and finally, reflecting and discussing. However, students move through these processes on their own, and in less clearly defined patterns.

This type of complexity renders the segmented descriptions of individual skills or tools inadequate. To offer a clearer picture of the nature of the system, we describe a short, realistic usage scenario with multiple users employing multiple tools.

Over the course of the project, teams of researchers across several countries have conducted extensive classroom trials with the Metafora system with various challenges and at various stages of implementation (see section 5 for further details). One or more researchers from the project team have always been present in these trials acting as participant or observer, with their main role being to ensure that the technology is functioning, probe students’ responses where appropriate, and observe teachers’ and students’ reactions and methods of incorporating the system into their lessons. However, it is worth mentioning that in general, Metafora activities involve a blended approach where some of the work is undertaken in classroom and some as homework.

The data collected from these trials have been analyzed and used to identify successive improvements and enhancements to both the technical environment (the system's tools) and the pedagogy underlying Metafora.

The following composite scenario demonstrates the use of Metafora tools and explains how Metafora promotes L2L2. This scenario is based on real data from several of these trials, to highlight a range of interactions with the system and the relation to the L2L2 pedagogy presented in section 2. However, the challenge, number of participants, and the scale of discussion and planning activities are deliberately limited here to offer a succinct summation of student work as related to system functionality.

The Challenge

In this example, the assignment given to students involves using the Juggler microworld [31]. A group of 4 students is divided into two teams: red and green (corresponding to the color of the balls and bases, as shown in Fig. 3). The challenge for each team is to make their 'ball' hit the opposite 'base' (meaning the red ball should hit the green base and vice versa), and further to understand generally how this is accomplished (i.e. how you can make any ball hit any base). Students are asked to plan their activities using the Planning/Reflection tool, to use juggler to understand and solve the challenge, and to use LASAD when they feel the need to communicate complex ideas within their teams.

When students first enter the tool, both groups immediately start with the Juggler tool (by clicking the "Juggler button on the left-side Metafora panel, Fig. 3). Each team begins their own experimentation by choosing different values for different variables available in Juggler (angle, azimuth, etc. – see [31] for more details pertaining to the specifics of this physics-based microworld). As the students explore possibilities in this microworld, they inherently confront their pre-conceived notions and misconceptions about three-dimensional motion.

Discussing Initial Ideas and Findings

As time passes, the red team more quickly grasps the variable adjustments needed to solve the problem, and finds the appropriate settings to hit the green base. They announce their success and their "solution", their current variable settings from juggler, in LASAD. The green team has not found an adequate solution yet, and so they ask questions within LASAD (Fig. 6). They ask the red team if the same parameters work to make the green ball hit the red base. Here we start to see the L2L2 principles in action. The green team considers that they need help and request it. The red team, being the first to offer a solution, takes a temporary role as implicit leader and help-giver, offering suggestions and trying to help the green team understand their solution. They do this through shared artifacts, giving information about the microworld parameters. We also see the two-way power of the collaboration: through the questions of the green team, they prompt the red team to consider both crucial conceptual and organizational aspects that have been somewhat overlooked by the red team. The green team's questions push the red team to explain whether their results apply in many situations, or only one, a key scientific concept of generalization. Their questions about the methods used by the red team to find a solution prompt the red team to reflect, and realize they are not sure exactly how they found their solution. The discussion continues and eventually prompts both teams to move to the planning tool.

Plan Formulation

Both teams now visit the Planning/Reflection tool together to try to form an overall plan as a group (Fig. 7). They all agree that their first stage was to test the model they had been given. They add to this a clarification that they are testing in an attempt to "change properties on the ball to make it hit the other base". Now, each team creates its own experiment card, but here we see two dif-

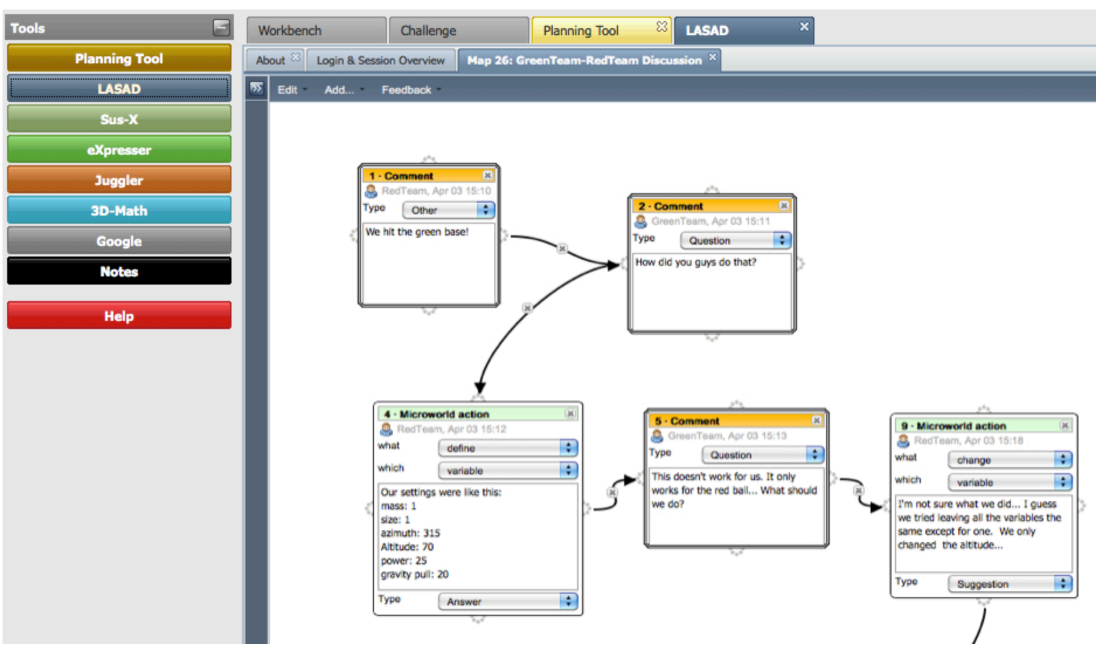

Fig. 6. Student discussion within LASAD where they share information about their microworld artifacts and higher-level ideas of how to accomplish tasks in Juggler.

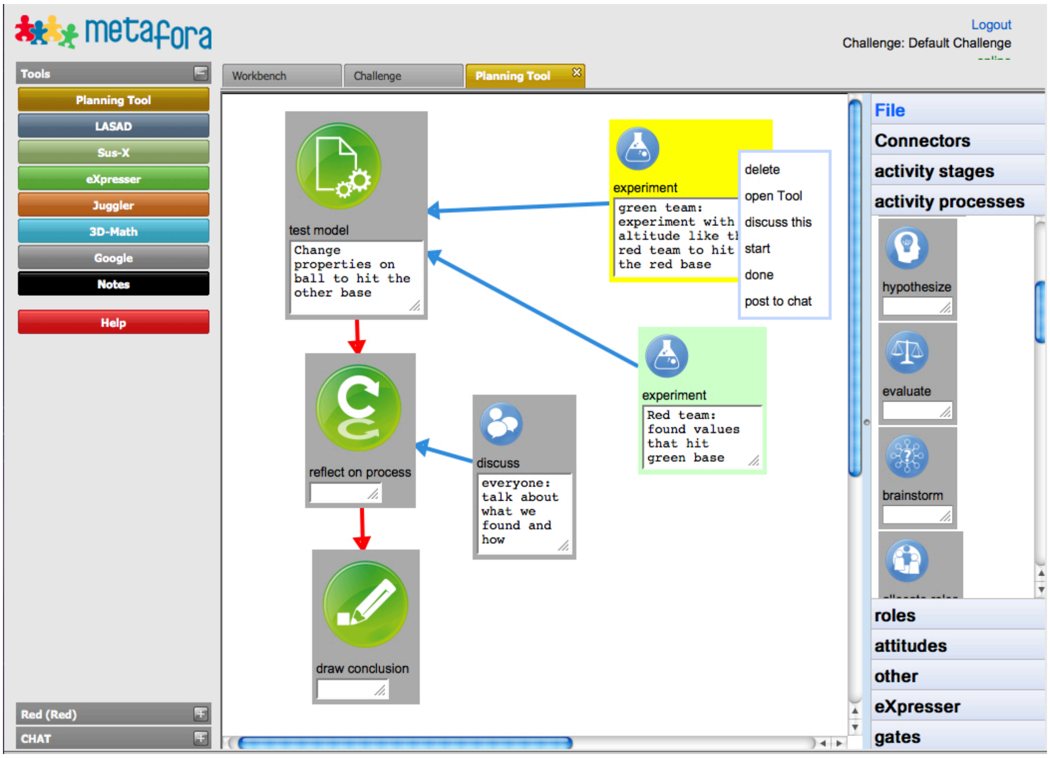

Fig 7. The plan formulated by students in the given scenario. The activity processes to the right are colored differently to denote that they are started (top) and completed (bottom), respectively. The context-sensitive right-click menu is also shown, as a user right-clicks on the top-right activity box.

ferent uses of the same type of card. The red team is merely reflecting on what they have already done, and so they note that they have found the values to hit the green base. Therefore, once they create this card, they right-click on the card and mark it as *done*. The card changes color to light green to acknowledge that it is complete. Here we can see how this planning reflection space can be used to summarize and reflect on past activities.

The green team is not reflecting, but actively considering their next step, which will be to experiment more specifically with the altitude parameter in juggler, as they learned that this is how the red team succeeded. Now they decide to enact this step, so they right-click on the card, and mark it as *started,* which colors the card yellow. They then right-click this experiment card again, and choose *go to tool* from the menu, which returns them to the microworld for experimentation.[3] This behavior demonstrates how the Planning/Reflection tool can be used as a central organizing location as well as the gateway to other tools.

The red team decides that, rather than move back to the microworld, they will remain in the planning tool for now, extending the plan into the future. They add the cards *Reflect on process* and *Draw conclusion* as they see both of these steps as necessary to complete the challenge. They add a *Discuss* card to note that they will have to discuss their findings in order to have any kind of successful reflection. Here we see standard planning activity, picking next steps and ordering them appropriately. The Planning/Reflection tool equally supports all of these varied uses.

Continuing the L2L2 Process

Work proceeds in this manner as students continue with the challenge. They move opportunistically between tools, having moments where they are brought together in a specific collaborative space to share ideas (at times of their own accord or as instructed by the facilitator).

All the while, the students are implicitly and explicitly practicing their skills at learning to learn together: taking on leadership roles when necessary, mutually engaging in planning and meaning generation through shared artifacts, asking for and offering help to one another, and reflecting on both the content which they have learned as well as the process by which they have learned it. This type of complex, engaged interaction is a true demonstration of the concept of learning to learn together, and therefore, the ultimate goal of both the pedagogy and the software system that comprise the Metafora project.

5. Discussion and Future Work

In this paper we have described Metafora, both a pedagogy and a platform to promote Learning To Learn Together. We have highlighted some central skills from the pedagogical theory that underlies our system, and detailed the tools in the current Metafora platform and how these tools relate to and support the acquisition of the

[3] This right-click menu is context sensitive, and offers the *go to tool* menu option because the *experiment* card is related to the Juggler microworld tool for this specific challenge. In a similar way, all tools can be related to specific cards for challenges.

L2L2 skills. Finally, we have given a brief composite walkthrough of a possible usage of the tools constructed from real classroom observation. We demonstrate through these descriptions how the system and pedagogy fulfill our goal of designing an environment that enables, promotes, and makes explicit the higher-level learning skills we term Learning to Learn Together.

The system has been used extensively thus far with students in the classroom to feed our understanding and help refine our concepts of both the theory of L2L2 and the software system that can support it. Pilot experimentations have been conducted in four countries by various project teams including: the Hebrew University of Jerusalem, Israel; the London Knowledge Lab, the Institute of Education, UK; University of Exeter, UK; and the Educational Technology Lab, National and Kapodistrian University of Athens, Greece. Each of these teams has conducted a series of 5-10 hour experiments with small cohorts of students (around 5 – 10) using successive versions of the platform. The results of these pilots were fed back both to the technical and pedagogical teams in an iterative fashion to improve the system. At the time of this writing, we have also begun main studies on a much larger scale (groups of 15 – 20 students or whole classes of more than 30 students in some cases), using the system refined by the insights gained from the pilots. These ongoing studies work with cohorts of students over longer periods of time (2 – 3 weeks) with activities undertaken both in class and as homework. As this paper is concerned specifically with the L2L2 pedagogy and how the design of the Metafora system addresses the emerging requirements, we refer readers to [30], [35], [36] for more detailed pedagogical analysis. We do, however, offer some brief insights from our experiences thus far.

Considering the data we have collected in our early studies, we have observed signs of success with the Metafora approach. During our pilot studies, from which we have already collected and analyzed data, we did not expect of course that students would master L2L2 skills in the limited duration they used the Metafora platform. This is a process that requires time and appropriate pedagogic support. We have already observed, though, even in these short spans of time, students' behavioral changes as they use the system, noting an increase in planning and discussion activity as they grow accustomed to the tools Metafora provides and the skills that are exercised when using the system.

We consider again our research question – *How should educational technology be designed in order to bring students' attention to and promote learning to learn together*? – in light of the results of these pilots and full-scale studies. We have observed time and time again the need for explicit instruction and scaffolding on the meta-level learning skills we have described in Section 2. Without this support, we see many students ignore planning steps, fail to recognize the learning goals related to meta-learning, and fail to reflect on the way they collaborate and support each other as a team. Other projects do not face the same dilemma, as they offer predefined steps to the inquiry process, e.g., [4], [6]. Providing a learning plan that is defined by teachers or system designers can help to guide students' focus, but does not necessarily support their reflection on how and why they engage in this process. We argue that students need to be able to define and reflect upon their learning plans as in order to focus their attention on the meta-level and, in particular, on the L2L2 process.

We also recognize that the tight integration of tools in our system explicitly supports students engaging in the higher-level skills of L2L2. The integrated tools support sharing, comparing, co-constructing, seeking and offering help. We strive to make group inquiry and collaboration the central and continual mode of operation, rather than individual inquiry, as in e.g., [6]. The pilot studies have shown that even tighter integration of the tools would be beneficial, as students can miss important learning opportunities when moving between contexts or work in different tools than their learning partners. This is a symptom of a larger concern. We recognize the general issue that, as other research has also shown [37], [38], such complex and open-ended environments introduce new challenges, possibly resulting in confusion. Teachers also face unique challenges as they find it difficult to monitor so many groups of students simultaneously [39], particularly when working asynchronously.

Keeping all of these issues in mind, our objective as we move forward is therefore utilize intelligent analysis of the students' interaction in order to encourage focus and reflection on these higher-levels aspects of L2L2 in the Metafora platform. This support will be based on identifying and visualizing indicators of student work produced by the different tools' analysis systems. These indicators are collected on different levels of granularity, from low-level activity indicators (statements marking student actions) to high-level landmarks (noting when students achieve goals or face recognizable difficulties within the tools). These indicators are collected by a cross-tool analysis component that can recognize patterns, offering higher-level feedback about overall L2L2 behaviors in the system as a whole. These same indicators can also provide useful information to teachers to increase their awareness of student activity and offer notifications of potentially interesting L2L2 activity. In [30], we present the first steps towards this intelligent analysis, and a potential use case demonstrating how such a system could support key L2L2 behaviors, specifically help-seeking and help-giving.

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