for instance we adjusted the assignment load over the course of the term.

The overall course structure consisted of a 1.5-hour weekly team-taught lecture, followed by weekly 3-hour labs of practice-based, hands-on learning activities. Instructors and TAs provided regular feedback to individuals and project teams. Weekly readings and a set of assignments provided the scaffolding necessary to prepare students to undertake a team-based project that integrated the fundamental elements of spatial thinking and graphical representation learned over the term. Computer modeling software (SolidWorks) was gradually introduced over the term enabling students to build confidence in those aspects of the tool necessary for the final project [16]. The course was delivered in a face-to-face format and course materials (lecture notes, video clips, and web-links to interesting examples) were distributed using the university's Learning Management System, WebCT. The assessment strategy incorporated weekly lab assignments, mid-term and final exams, and a group-based major project (see Appendix A).

CONTEXTUALIZING SPATIAL THINKING

Course Content

Students were introduced to the nature of spatial thinking through discussions of real-world examples and presentations on tools used in spatial thinking. This was followed by an exploration of spatial thinking concepts including identification of spatial entities (objects), mental and on-paper representation, translation and rotation, assemblies, associations between objects, and objects and space, representation tools, and reasoning. We were particularly committed to the value of sketching in learning spatial skills. Thus, students were exposed to sketching techniques (freehand and using computer applications). Both techniques are imperative to spatial thinking as they complete the representation used in communicating ideas not only to others, but also to themselves.

Students learned basic skills in contour sketching, and in drawing straight lines, basic shapes (rectangles, circles), and curved lines. As the course progressed, more advanced concepts in visualization and spatial thinking, such as proportions, shape and geometry, coordinates, properties of points, lines, circles and arcs were introduced.

Following this introduction, a considerable portion of the course was devoted to (technical) visualization methods to control representing the complexity of spatial compositions through translating between 2D and 3D and using multi-view projections, cross-sections and axonometric projections (isometric, perspective). Details of the methods were presented in lecture sessions, along with a variety of in-lab and homework assignments and were a vital, integral component in supporting students in developing their spatial skills.

In order to include precision and accuracy in representations, spatial entities must be located in space and geometric properties (such as sizes) must be communicated. We introduced dimensioning basics. The course is also required to meet the needs of the Mechatronics program: the team used SolidWorks as the computer modeling system. Concepts of constraints, degrees of freedom, and modeling theory were introduced in the context of this tool.

Integrated Laboratory Activities and Assignments

Our main objective in developing laboratory activities and assessment was to create opportunities for students to apply the knowledge gained in lectures. Initially students designed a two-axis gimbal mechanism using Lego Digital Designer [17]. (A gimbal is a device with rotating rings, commonly used in gyroscopes). Although students at this early point in the course had limited exposure to material regarding spatial thinking, they found the software easy to use since it was a digital form of a familiar toy. The goal was to discuss operations fundamental to spatial thinking, such as identification of objects, composition, rotation and translation, as well as static and dynamic relationships between spatial entities (Figure 2).

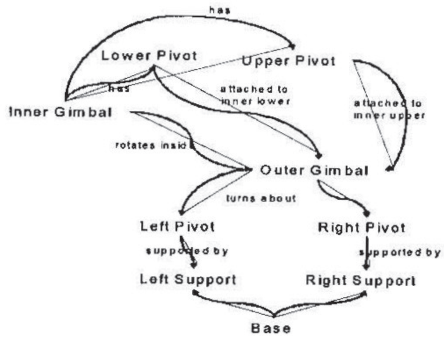

Figure 2. Two-Axis Gimbal: Two-Axis Gimbal System Sketch and Concept Map.

Students identified gimbal sub-assemblies and their relationship to each other, and represented these objects using a concept map [18]. The students then used their map to help them create a gimbal using the Lego software. The nature of Lego required that students also consider the necessary building blocks to create each sub-assembly. Building on this exercise, a second lab required students to create a gimbal using real Lego blocks (Figure 3). Although not a primary learning objective, students learned the limitations of software representations: during the transition from digital to physical, many had to adapt their designs to properly function in the real physical world.

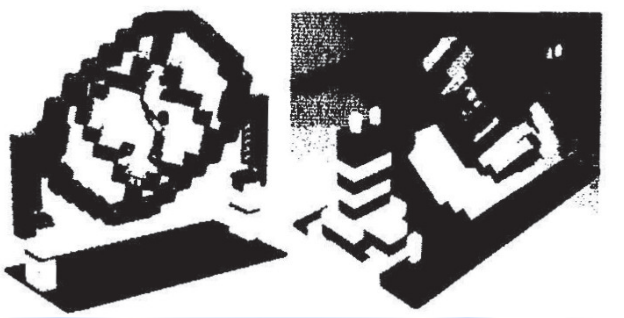

Figure 3. Two-Axis Gimbal: Digital (left) and Physical Lego Models.

To complete the foundation activities, the students undertook exercises designed to support communicating spatial information via free-hand sketches using techniques presented earlier (multi-view, isometric views). The Lego exercise was followed by a number of lab activities that incrementally introduced spatial thinking ideas through various multi-view and related sketching tasks.

The final six lab activities were dedicated to the course final project: building an animated mechanical toy (AMT), commonly referred to as automata [19]. Such toys consist of an articulated figure or model that is set into motion using a manual crank-based mechanism contained in a box. Students were introduced to AMTs as well as the necessary mechanisms: cranks, cams, gears, and friction drives needed to animate them, in lectures. Throughout this process, students applied their knowledge in analyzing 'spatial' entities, describing their understanding through sketches, developing their AMT design through various representation techniques, applying fundamental spatial thinking knowledge and skills throughout the design process.

Learning to Think Spatially

The remainder of this paper illustrates the nature of the activities and outcomes associated with the final project. In this section we focus on the analysis and presentation of one student team project. To assess evidence of learning to think and communicate spatially, and to guide our analysis, we attempted to answer the following questions:

1. Did the students in this course learn to think and communicate spatially?
2. Did the final project assist students to integrate and apply the spatial thinking concepts and representational skills taught in the course?
3. What are the implications for course revisions?

Flying Fisherman: A Student Project

A team of three students completed the "Flying Fisherman" AMT. All three successfully fulfilled the course requirements (lectures, labs, individual assignments, exams) and the team was awarded an 'A-' for their final group-project. The project was representative of those produced by the teams in the course as it was neither the best nor the worst and it demonstrated the expected learning outcomes. The project was organized into four phases, and deliverables representing each phase were examined for evidence of spatial thinking using the components listed in the assessment map (Appendix B): a sketch, a concept map, a digital exploded view of parts, a physical model, and a written paper. The phases of the final project are not discrete; the process is more like a conversation between phases, where one phase informs or provides feedback to the other. That this information flow is bidirectional, with students often returning to an earlier phase to revise their work.

Phase I – Concept map and 3D sketch of proposed AMT: The concept map (Figure 4) accurately represents the mechanical box, figure, and relationships of parts to whole, suggesting that the students in this case successfully represented their ideas for a "flying fisherman" AMT with moving parts and assemblies that could work together to form a functional project.

The sketch, on the other hand, has misleading information: the box shown in 3D does represent the mechanism accurately, although the figure is represented accurately in 2D. Although the sketch is a "close enough approximation" the students may have had difficulty representing the mechanical system in 3D. Our hypothesis at this stage is that the more accurate the representation, the more likely the digital and physical models will be accurately and successfully realized. Developing accurate sketches takes time and practice.

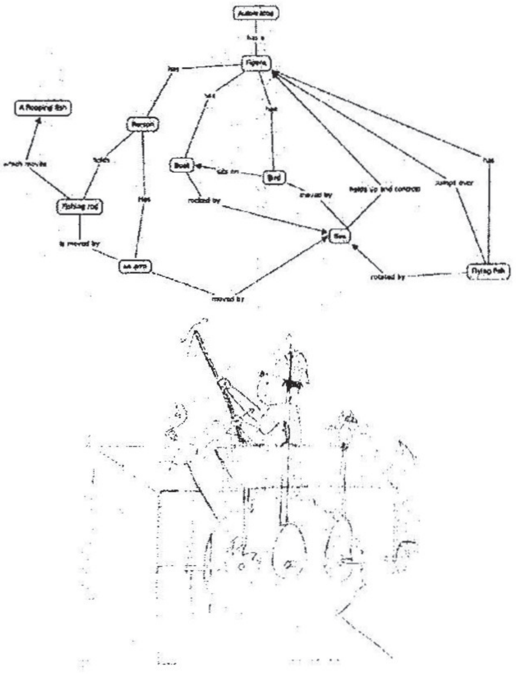

Figure 4. Flying Fisherman AMT: Concept Map (top) and 3D Sketch.

Phase II – Designs represented in a digital environment: Figure 5 shows the exploded view of parts proposed for the whole AMT. In moving from sketches to a digital model, students had to demonstrate size, location, and spatial properties of parts, proportion, and geometry. The digital model maps to the sketch. Initially, we required each student to model the parts, but due to time constraints and difficulty in assessment we changed it to a group requirement. As the resolution of the representations increases, students face different challenges – e.g., no real dimensions in sketches, accuracy was not an issue but once they moved to digital models dimensioning became an issue. Scale and proportions become important. Moving from digital to physical, students had the parts but now materials and their properties become important – assembly order is also a reality.

Phase III – Creating the physical model: Evidence of learning to think spatially is demonstrated by comparing how well the physical model conforms to the digital model created in SolidWorks. For instance, flat parts have been added to the cams and supports on the followers (see Figure 6). Understanding the relationship between parts with respect to physical forces was not possible in the digital model the students designed, but in building the physical model, they realized forces would act upon the pieces and impact the functionality of the mechanism; therefore, they modified the physical model. This team made good decisions in selecting materials for the construction of their model as it is still "alive" after 6 months and many demonstrations.

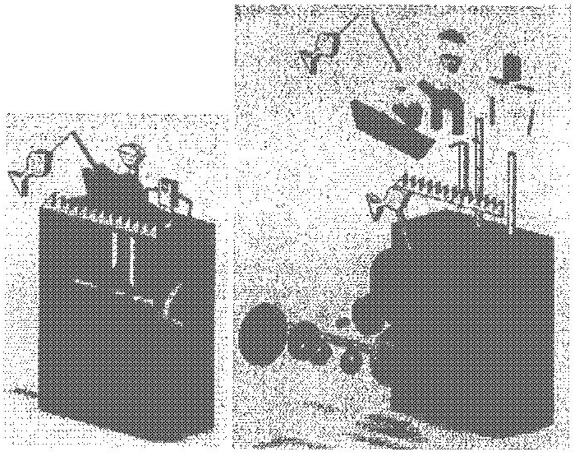

Figure 5. Flying Fisherman AMT: Assembled (left) and Exploded Views of Digital Model.

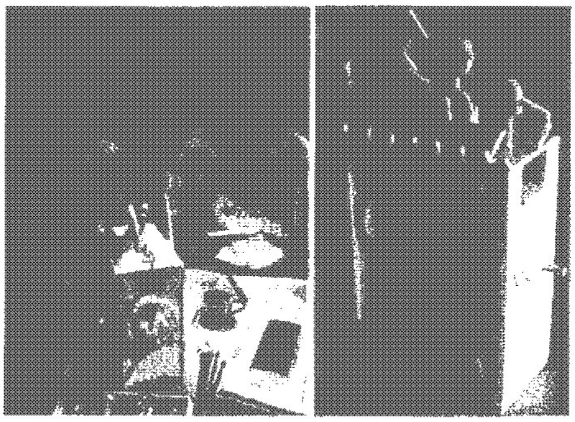

Figure 6. Flying Fisherman AMT: Physical Model.

Phase IV– Reflections paper on spatial thinking: A review of the written submission suggests that spatial thinking skills helped them differently in each stage of the project. In the digital environment, their spatial thinking skills did not incorporate real world factors even though part-whole relationships were established at an abstract level. The notion of degrees of freedom, dimensioning, and locating parts in the digital design were considered. In the physical environment of Phase III, spatial thinking skills helped them solve spatial problems. The following quotations come directly from the reflections of the students:

1. In regard to order of assembly: "However, in the physical model, we had to measure carefully by hand to ensure pieces would fit. Finally, having all the pieces together, we still had the problem of the flying fish gear system failing due to the tension force of the elastic".
2. In determining the selection of materials and impact of the forces of gravity: "we wanted to keep everything light".
3. In managing the forces discovered in moving from a digital to physical model: "we used some wire, strings and tape for some of the minor adjustments and movements".

Lessons Learned

Analysis of the final group project suggests that course objectives were achieved by this team of students (see Appendix B). By including the 3D modeling tool (SolidWorks) the course also met the requirement that students learn modeling skills. However, learning to use this particular tool for spatial thinking comes at the cost of extra time due to its complexity. The complexity of SolidWorks was a challenge for new users and—although we focused only on necessary features—students still required considerable support and time to use the software. We observed that migrating from sketching and Lego to full-featured computer modeling, that requires more than a simple selection and snapping of parts into assemblies, is more challenging for some students. Despite concerns that this tool may not be the best choice for teaching spatial thinking, students did learn to use the basic functions to meet the curriculum requirements.

Important lessons were learned by the course team that will influence future delivery of this course. One of these is the need for high-level of expertise required from the TAs to successfully support students learning. In delivering the course to a large class-size and first time, we had a TA team meeting this requirement. However, we will need to provide more training on the modeling software and a TA guide is currently being produced that will include the laboratory exercises as well as additional evaluation rubrics to ensure consistency in grading. These are also necessary for continuity.

The team approach to design and teaching proved both challenging administratively and pedagogically. Currently students at SFU can only register officially (for grading purposes) under one instructor and teaching credit. Therefore, an overall teaching assessment for the course was not possible, at least through formal channels. From a pedagogical perspective, the challenges of a large team included a significant effort simply to coordinate and communicate. We relearned Fred Brooks' lesson on this [20] the hard way over the course of the first offering, and will build in time for this in future offerings.

Overall, the experience of designing and teaching this course has been highly positive for both the instructors and the students. We have challenged many of the current structures of the university and made demands on ourselves that exceed the efforts normally associated with developing and teaching an undergraduate course.

CONCLUSION AND DISCUSSIONS

The first offering of our course succeeded in helping students from diverse backgrounds and skill-levels learn to think and communicate spatially. Over 96% of the students who completed the course received a passing mark (D or better), with very low numbers of failures; 88% passed with C+ or better, and 62% B or better. We believe that the unique focus of this course for early undergraduate university students goes a long way towards advancing our understanding of what is possible to achieve in teaching complex concepts and skills in large enrollment courses.

Although our class size was large and the course subject was novel for undergraduate curricula, we created effective learning environments in our laboratory sessions where students could directly interact with an instructor, a TA, and their fellow classmates. By providing hands-on experience, students had the opportunity to practice and communicate with each other. The existence of a major course project required initial laboratory sessions to be focused on providing students with the skills necessary to complete their AMTs.

One of the main sources of satisfaction for students, TAs, and instructors alike, was seeing the final projects work—there were more than 50 projects completed successfully. Because students were creating an AMT of their own design, they felt a sense of ownership over the project so that concepts taught throughout the course were no longer the main focus, but were tools needed to arrive at a functioning AMT.

While the course team is reasonably satisfied that we achieved the main course objectives, our next offering of the course is currently undergoing further reflection and refinement as we seek to incorporate the many lessons learned from the course described in this paper. One of our major successes lies in the fact that all the course instructors are eager to return to the classroom to effect the improvements.

ACKNOWLEDGMENTS

We are particularly indebted to our TAs, Bernadette Currie, Tim Chueh, Yin He, Jimmy Koo, Maryam Mokhtarmaleki and Roham Sheikholeslami, all of whom gave unstintingly of their time and expertise, much beyond their paid hours. Without their efforts, we could simply not have presented the course as described. In addition, Ms. Currie's expertise in SolidWorks was invaluable, and appreciated. We also thank the students of TECH 106: Spatial Thinking and Communicating, for the many lessons they taught us about teaching and designing this course. Last but not least, we would like to acknowledge that all the authors of this paper, irrespective of where their names appear, have contributed significantly to its planning, writing, and revision.

REFERENCES

[1] National Research Council, *Learning to Think Spatially*. Washington, DC: The National Academies Press, 2006.

[2] R. G. Golledge and R. J. Stimson, *Spatial Behaviour: A Geographical Perspective*. New York: Guilford Press, 1997.

[3] N. S. Newcombe and J. Huttenlocher, *Making Space: The Development of Spatial Representations and Reasoning*. Cambridge, MA: MIT Press, 2003.

[4] A. Casati and A. C. Varzi, *Parts and Places: The Structures of Spatial Representation*. Boston, MA: MIT Press, 1999.

[5] R. G. Golledge, "Do People Understand Spatial Concepts: The Case of First-Order Primitives", in *Proceedings of the International Conference GIS - From Space to Territory: Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, September 21-23, 1992, pp. 1-21.

[6] E. Y-L. Do, GIS 172: Visual Reasoning, URL: http://code.arc.cmu.edu/visual. Last viewed on April 22, 2008.

[7] J. Sharp and L. W. Zachary, "Using the van Hiele K-12 Geometry Learning Theory to Modify Engineering Mechanics Instruction", *Journal of STEM Education Innovations and Research*, vol. 5, no. 1&2, 2004.

[8] A. B. Dunwoody, APSC 151: Computer-Aided Engineering Graphics, URL: http://courses.engineering.ubc.ca/apsc151. Last viewed on May 19, 2008.

[9] R. Golledge, GEOG 581: Concepts for Spatial Thinking and GEOG 583: Spatial Analysis and Modeling, URL: http://college.usc.edu/geography/courses/graduate.html. Last visited on May 12, 2008.

[10] L. V. Williams, *Teaching for the Two-Sided Mind*. Prentice Hall, Inc., 1983.

[11] J. F. Voss and J. Wiley, "Acquiring Intellectual Skills", *Annual Review of Psychology*, vol. 46, pp. 155-81, 1995.

[12] I. A. Miller, *Insights of Genius: Imagery and Creativity in Science and Art*. New York: Copernicus, 1996.

[13] B. Johnston (Ed.), *My Inventions: The Autobiography of Nikola Tesla*. Hart Brothers Publishing, 1982.

[14] J. H. Mathewson, "Visual-Spatial Thinking: An Aspect of Science Overlooked by Educators", *Science Education*, vol. 83, no. 1, pp. 33-54, 1999.

[15] TechOne Program, URL: http://students.surrey.sfu.ca/techone. Last visited on May 19, 2008.

[16] S. Tickoo and D. Maini, *SolidWorks 2007 for Designers*. CADCIM Technologies, 2007.

[17] Lego Digital Designer, URL: http://ldd.lego.com. Last viewed on March 30, 2008.

[18] J. D. Novak, "Concept Maps and Vee Diagrams: Two Metacognitive Tools to Facilitate Meaningful Learning", *Instructional Science*, vol. 19, pp. 29-52, 1990.

[19] R. Peppé, *Automata and Mechanical Toys*. Crowood Press, 2002.

[20] F. Brooks, *The Mythical Man-Month: Essays on Software Engineering*. Addison Wesley, 1975.

Appendix A: Course Map

TABLE I

Course Assessment Map for Spatial Thinking and Communicating

TECH 106: Spatial Thinking and Communicating – Course Assessment Map

Audience Characteristics:

- First-year university students from diverse backgrounds with a range of abilities and interests.

Course Intent:

- Expose students to spatial thinking concepts, graphical representation and communication.
- Provide a foundation of basic knowledge and technical skills for students to envision 3D structures, visualize and think in 3D, analyze spatial thinking problems using sketching, digital and physical modeling.
- Enhance the students' spatial thinking abilities and skills (see and understand the world in new and useful ways).

Course Learning Objectives	Assessment Strategy	Student Deliverables
By the end of this course, it is hoped that students will be able to: 1. Describe and use spatial thinking. 2. Use graphical representations and communication in different problem domains such as engineering, arts and business. 3. Examine and interpret 3D representations. 4. Visualize and define spatial problems and proposed solutions. 5. Create and manipulate 2D and 3D representations of their solutions to given spatial problems. 6. Select representation tools and techniques and make association among them when working on problems requiring spatial thinking. 7. Use a computational modeling tool (such as a computer-aided design system).	Assignments: • Labs and homework: 30% • Mid-term exam: 20% • Final exam: 25% • Project (team-based): 25% **Principles of assessments**: • Test for knowledge of concepts. • Scaffolding skills and concept development. • Practice-based feedback from instructor/TA. • Independent and team-based. • Peer-to-peer feedback. • Peer-assessment.	Activity-based individual Labs and Homework: • Concept map. • Digital gimbal model. • Physical gimbal model. • Reports. • Plan. • Pencil and paper sketches using grid paper. • Sketches showing isometric views and perspectives. Activity-based Group Project: • Phase I – Representing ideas in sketches and annotation. • Phase II - Parts and Whole – Digital AMT in SolidWorks. • Phase III – AMTs Realized – Digital and physical models. • Presentation & competition.

Resources:

- Sketching with pencil and paper, digital Lego software, physical Lego parts, CAD software (SolidWorks), physical materials.
- Presentation technologies (ppt, etc.).
- Learning Management System (WebCT used in delivery of course).