TEACHING SIGNAL PROCESSING ACCORDING TO WHAT YOUR STUDENTS KNOW

Geoffrey L. Herman

University of Illinois at Urbana-Champaign

ABSTRACT

Many professors and instructors fear (or rejoice) that the Internet will someday make their role as teacher obsolete. While the Internet is an incredible repository of knowledge, it is not a repository of experience. In this paper, I present how instructors can leverage the information on the Internet to empower themselves to apply their experience to better teach students according to what their students know. This interplay can increase learning, student engagement, and create new ways to assess the quality of teaching.

***Index Terms*—** Signal processing, Engineering education, Internet

1. INTRODUCTION

> If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly. - Ausubel [1]

Two great hindrances to student learning are the incorrect preconceptions that students bring into a course and the incorrect interpretations that students make when first presented with novel course material. Ausubel summarized this finding of student learning in 1978, yet little research has been published that documents the common student misconceptions and difficulties of many disciplines. Therefore, the responsibility for discovering students' misconceptions and devising remedies for these misconceptions falls upon the instructor. This responsibility can easily be left unfulfilled due to the time demands of preparing lectures, homework assignments, and examinations; grading assignments; holding office hours; attending committee meetings; and everyday life.

In a traditional lecture and homework based course the flow of instruction and feedback may resemble the chart in Figure 1.

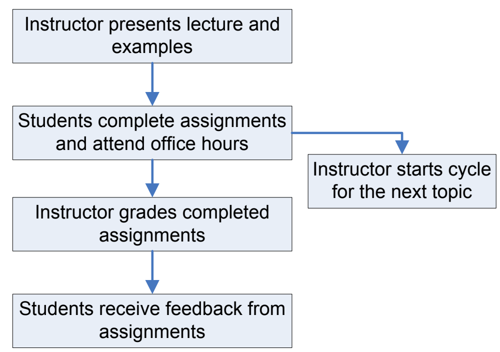

Fig. 1. Flow of instruction and feedback in a traditional lecture based course

During this instruction cycle, there are few opportunities for the instructor to ascertain what the students know and base instruction around that knowledge. In most cases, the instructor can first ascertain a deep level of student understanding only when grading homework — after formal instruction on the topic has ended. Instructional methods such as "clicker" questions and other interactive engagement exercises can increase the instructor's awareness of student knowledge in the classroom, but these methods require the instructor to think quickly and change course content "on the fly." Ultimately, lecture based courses were not originally designed to allow instructors to base instruction upon what the students know but rather on what the instructors know.

In order to adapt instruction to student knowledge, instruction needs to switch paradigms from a transmission model (learning is received when instructors transmit their knowledge to their students) to a constructivist model (learning is primarily created by constructing new knowledge upon old knowledge already possessed by the student) or a social model (learning primarily happens in social interaction and discussion) [2]. Since pedagogical activities based on social and constructivist models increase learning, how much more could entire courses based on these models increase learning [2]?

In this paper, I present my first attempt to design and teach a course where instruction was based primarily on learning what my students already knew and then teaching them accordingly. The method I used essentially inverts the role of the classroom: Lecture takes place outside class and homework takes place inside class. Because of a lack of *a priori* IRB approval, I cannot present original student data from classroom assignments or student misconceptions directly in this paper. Instead, based on my personal data collected contemporaneously, I will focus on describing the course design and offering insights into how the blend of online and in-class techniques improved my ability to learn what my students understood.

2. BACKGROUND

In 1992, Hestenes, Wells, and Swackhamer published the Force Concept Inventory (FCI) [3]. The FCI is a multiple-choice conceptual assessment that requires students to choose between correct conceptions and documented, common student misconceptions about the force concept. The FCI was instrumental in motivating the adoption of interactive engagement pedagogies [4, 5] and raising awareness of students' misconceptions in physics education.

Because the FCI changed physics education, science, technology, engineering, and math (STEM) educators have attempted to replicate the impact of the FCI in their own disciplines by creating concept inventories (CIs). The Foundation Coalition [6], in particular, championed the creation of many CIs, including the Signals and Systems Concept Inventory (SSCI) [7]. The SSCI has shown that interactive engagement teaching methods can improve student learning in signal processing courses [8, 9].

The SSCI is a validated, reliable instrument that can empower instructors to learn a little about their students' knowledge of signals and systems, but it has its limitations. While the SSCI documents many common student mistakes, it is not intended to be a comprehensive assessment and therefore does not provide insights into every topic in signal processing that a student may need to learn [7]. In addition, the SSCI is primarily intended to be a pre-course and post-course assessment tool for comparing the effectiveness of different pedagogical techniques. So, while the SSCI can estimate the level of conceptual knowledge that students possess at the beginning of a course, it can be unwieldy to use the tool to provide estimates of students' knowledge throughout the course.

An emerging teaching technique based on a constructivist model of learning is the "Just-in-Time-Teaching" (JiTT) method [10]. When using JiTT, instructors create "warm-up" problems for students to complete outside class. Instructors then collect students' responses through an online submission mechanism "just in time" for class. Students' responses become the topic of discussion for a portion of the class. The remainder of class is devoted to allowing students to work through more complex problems under the supervision of the instructor and teaching assistants. In addition to improving learning, JiTT has been shown to improve student study habits and preparation for class [11].

3. COURSE STRUCTURE

At the University of Illinois at Urbana-Champaign, all students majoring in electrical and computer engineering take ECE 210, which teaches circuit analysis for the first half of the course and introduces analog signal processing during the second half of the course. After completing ECE 210, students can take ECE 410: Digital Signal Processing, as an elective. Students typically take this course during their junior or senior year.

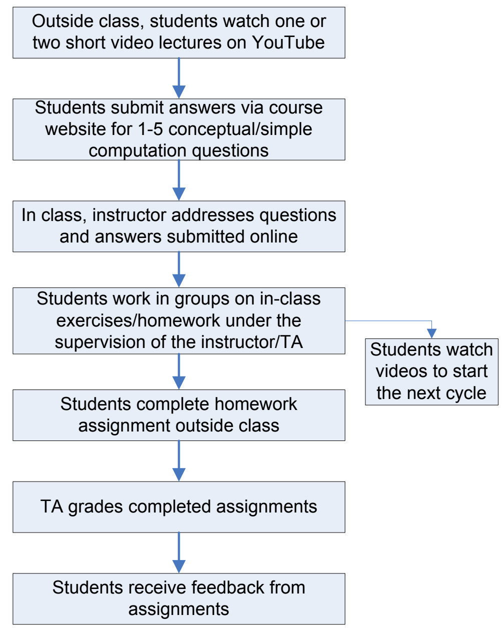

Fig. 2. Flow of instruction and feedback in a Just-in-Time Teaching based course

During the summer of 2010, I taught ECE 410 and used JiTT methods as the basis of the course design. Students watched video lectures and answered online homework questions outside class and then met in class to discuss their answers and practice solving problems. The course had 21 students enrolled and met Monday through Friday for 75 minutes for eight weeks. A graduate teaching assistant (TA) graded the written homework assignments, helped with in-class problem solving sessions, and held additional office hours.

Since my primary goal for the course was to base instruction upon students' questions and students' knowledge rather than strictly upon covering course content, the first day of class was devoted to administering the SSCI to get a baseline of student knowledge. After the first day, the instruction cycle resembled the chart in Figure 2.

3.1. Video lectures

As the Internet and social media grow and become more pervasive, the content knowledge of most academic disciplines is readily available at no cost to our students. Because information about Fourier transforms, sampling theory, and filters can be accessed anywhere, the role of the instructor as a provider of knowledge has been greatly diminished. The Internet cannot, however, replace an instructor's expertise and experience. Because of this shift in paradigm, I decided to let the Internet serve as my student's repository of knowledge and use class as the time to apply my experience to discern what my students were struggling to understand.

Students watched short (3-7 minute), conceptual video lectures. The video lectures were produced using a web cam, tablet PC, Camtasia, and Microsoft PowerPoint. The completed videos were posted on YouTube (http://www.youtube.com/user/IllinoisDSP).

The videos were streamlined to present only the core of the lecture's topic and thus contained no example problems. The lectures were also created based on principles from cognitive load theory (CLT). CLT dictates that the visual and audio content of multimedia videos contain only complementary information and never replicate each other [12, 13]. Because the eyes and ears can both process information separately, presenting redundant information to both receptors reduces the amount of information the student could receive. In addition, if the information is complementary, the student can more easily develop an association between the images and the spoken words. These associations promote learning. As an example, if the video displayed the formula for the Fourier transform, the audio narration would not read the variables of the expression, but would identify the name of the formula and describe its purpose (e.g., "We then use the Fourier transform to convert our signal from the time-domain to the frequency-domain).

The video lectures offered several advantages over traditional lectures. First, the video lectures presented material to students in much less time than it would take to present the same material in the classroom. Second, students could pause and replay the portions of the lecture that they found confusing. Third, if students wanted to learn more about the video content, YouTube linked students to video lectures on the same topic previously posted by different instructors.

3.2. Online assignments

Students are rarely motivated to complete non-graded assignments such as reading texts or watching videos, but these assignments are necessary in a JiTT teaching environment [14]. This problem of motivation can be effectively solved by directly connecting the content of classroom instruction with student responses or feedback from out-of-class course material. Via online submission, students submitted answers to a few conceptual questions. For every lecture, students also needed to submit a response to the following question.

> What is the one thing that confused you the most from this video lecture? OR What is one question that you would like me to answer in class?

Most conceptual questions were open-ended in form. Questions tended to fall into three categories: simple recall questions (e.g., List the advantages and disadvantages of using IIR filters instead of FIR filters.), relationship analysis questions (e.g., Does zero-padding reduce the size of the side-lobes of a DFT? Why or why not?), and fundamental calculation questions (e.g., Find the z-transform of $x[n] = \cos\left(\frac{\pi}{4}n\right)$ for $n = 0, \ldots, \infty$. Don't forget the ROC!).

Because answers were submitted online, I could use a variety of questions. In-class interactive engagement tools such as "clicker" questions are necessarily multiple-choice questions because of the capabilities of clickers. These types of questions are most effective when the answer choices are based on common student misconceptions and mistakes (such as those documented by concept inventories). Since signals and systems education research is relatively young (when compared with physics or mathematics education), there is little documentation of common student misconceptions to provide a basis for multiple choice questions. Online, open-ended questions allowed me to search for the common student misconceptions and mistakes and then address those deficiencies of understanding in class.

Students' answers to the online questions served as the basis for the first 30 minutes of in-class discussion. I would never explicitly review the lecture material, but would use the submitted answers as my link back to the material presented in the lecture. Before class, I compiled students answers and tried to diagnose the reasoning behind the most common wrong answers by using principles I had learned from previous misconceptions research [15]. Based on these misconceptions and common problems, I developed examples that I would present, and I created in-class exercises that students would solve individually or in ad hoc groups.

3.3. In-class exercises

Because research has shown that students learn more by debating and discussing problem solutions with their peers rather than listening to an instructor's explanation [2], students were also given time to interact with each other as they solved problems. The problems given during the in-class exercises were a combination of original problems written for class and problems taken from the assigned written homework. These problems were more complex than the online problems, but were still fairly short so that students could present their answers and receive feedback. While students solved problems, the course staff circulated among the students and addressed questions as they arose. Typically, students reported their solutions to problems after a fixed period of time.

The in-class exercises gave the course staff time to watch how students solved problems and encourage good problem solving strategies. By seeing students' solutions to the problems, we had yet another chance to diagnose students' level of understanding and adjust instruction to match what students knew.

4. IMPRESSIONS

While teaching the course, I maintained a teaching journal to document my impressions of students' problems and my own difficulties with implementing this new teaching method. An undergraduate research assistant also helped conduct two voluntary focus groups (one during the third week of the term and one during the last week of the term) where students were given an opportunity to voice their thoughts on the course. From these journal entries and focus groups, I share what I have perceived to be some best practices and some common student difficulties/misconceptions.

4.1. Best practices for implementing JiTT

Students need incentives to attend class: When designing the course, I decided to not make attendance a part of the grade, but decided to motivate students to come to class by promising to solve some of their graded, written homework problems in class. Unfortunately, the same 14 of 21 students regularly attended class, while the remaining seven students watched the videos but only attended quizzes and examinations. The lack of attendance was more disturbing to me than usual.

To make lemonade from the lemons, I tracked the grades of students who attended versus those who did not attend class, Following the weekly quizzes, I e-mailed the average grades of the two groups to my students. Students who attended class scored an average of two grade letters better than students who did not attend class. During the end of summer focus group, students revealed that watching the video lectures decreased their motivation to attend class, but the grade e-mail motivated them to attend. Towards the end of the summer, the average attendance increased.

Because students have seen the course material in the video lectures, many students have more reasons to not attend class. Instructors should include new incentives for attending class whether that be credit for attendance or more intrinsic motivations such as solving graded problems in class.

In-class problem solving sessions need structure and accountability: In-class problem solving sessions are most successful when there is clear structure and accountability. Structure can be provided by giving a reasonable time limit for solving problems, assigning groups and roles within the groups (e.g., in pairs, only one student is allowed to see the problem definition, but is not allowed to use a writing utensil, while the other student has the opposite role), or think-pair-share models work well. Accountability can be provided by selecting random groups to present answers, selecting random students to present answers, or assigning one problem per student/group and each student/group presents. If structure and accountability are not provided, students can quickly return to relying on others to transmit knowledge to them.

Develop a JiTT course/lecture videos over two semesters or use existing online materials: Converting from traditional lecture formats to JiTT formats takes time and planning. I would strongly discourage instructors from implementing a JiTT course the first time that they teach a course, unless they have an enormous amount of time to prepare. The development of lecture videos takes twice as long as it does to develop comparable in-class lectures. Online lecture videos can be implemented efficiently with the following steps.

1. Outline the flow of the lecture by creating PowerPoint slides (slides should have start with sparse (if any) text aside from equations and be rich with images).
2. Using the PowerPoint slides, write a script for the lecture (be sure to indicate where to pause!).
3. Record the audio narration of the video.
4. Record the PowerPoint slides so that the video complements the audio narration.

The development of good PowerPoint slides and scripts for a three to seven minute video can take three to four hours or more if you do not already possess the figures that you need to create the narrative of the slides. When slides and a script are complete, recording a five minute video will take one to two hours depending on the level of editing. Once the video is recorded, you still need to develop the conceptual questions and other assignments. In sum, I would budget to spend eight hours of preparation per class period!

I would recommend that instructors divide the preparation time over multiple semesters. For example, during the first semester, I would create the power-point slides, conceptual questions and other assignments. If possible, I would record my lectures during that semester and use those recording to develop the scripts for the lecture videos (these lecture recordings could also be used as an additional resources for future students). During the second semester, I would record the videos in place of preparing to lecture and re-use/re-package the same assignments from the previous semester. For example, split previous homework assignments into two parts and use one part for in-class exercises and use the other part for the homework assignment. After the second semester, I would focus on refining course materials as needed. If you find already existing videos, online content, or even a textbook that meets your needs for out-of-class instruction, this development time can be shortened.

The video scripts can be used to improve accessibility for all students, especially those with disabilities. If the PowerPoint slides and scripts are made available to students, they will waste less time searching through the video for the information they are looking for.

Include lecture wrap-ups and face-time: From the focus groups, I learned that students really appreciate having face-time (times where they see my face) and wrap-ups in the video lectures. Students said that the face-time made the videos more personable and enjoyable. I created face-time by using a web-cam and introducing and concluding the videos with a standard video blog style. Students wanted a short summary of the important concepts at the end of each video even though they could replay the video to review any necessary concepts. They said that the summaries helped them remember the content of the video and determine what was important for them to learn in the video.

4.2. Misconceptions and difficulties

During the term, I was able to identify some common student mistakes and misconceptions. Since I cannot present original student artifacts, I will list some of the common troublesome topics that I recorded in my journal and focus on discussing how I found these mistakes. As a quick aside, students were surprisingly adept at manipulating z-transforms, difference equations, manipulating FFTs, and other mathematically complex operations. However, students struggled to understand convolution, interpreting digital frequencies (both discrete and continuous digital frequencies), the difference between zero-padding and increased window-sizes, stability of parallel and series filters, and the effects of poles and zeros on the frequency response of a filter. Perhaps most alarming, students struggled with the concept that the Discrete-Time Fourier Transform (DTFT) of a real-valued signal or series is evenly-symmetric and periodic with period 2π.

Students possessed misconceptions about how sampling scales the magnitude of the DTFT of a digital filter. The digital cut-off frequency of the filter should be related to the analog frequency by the equation ω_0[rad] $= \Omega_0$[rad/s]$T[s]$, where T is the sampling period. The transformation of digital *signals* and digital *filters* to analog signals and filters both follow this scaling scheme. The transformations of the magnitude of the DTFTs of signals and filters to the analog Fourier domain are different. While the magnitude of the DTFT of a digital *signal* is scaled according by $1/T$, the magnitude of the DTFT of a digital *filter* is not scaled.

I first discovered these misconceptions by analyzing the submissions for an online conceptual question. The conceptual question asked students to determine the analog frequency of a digital system with sampling period T and a low-pass filter with cut-off frequency ω_0 and magnitude 1. In response to the misconceptions revealed by this question, I created several examples to use in class to illustrate why the misconceptions were invalid.

For example, students were given the Fourier transform of the input of a system ($X_a(\Omega)$) and the output of the system ($Y_a(\Omega)$). They were first asked to find the analog frequency response of the system $H_a(\Omega)$. Students were then asked to find the DTFTs of the input ($X_d(\omega)$) and output ($Y_d(\omega)$) given T. They then had to find the digital filter ($H_d(\Omega)$) that created $Y_d(\Omega)$ from $X_d(\Omega)$. Students were finally asked to compare and contrast $H_d(\Omega)$ and $H_a(\Omega)$.

Suppose that we want to use a digital filter to filter a band-limited signal $x[n]$. The system has the following specifications.

- $x[n]$ is band-limited to 6000 Hz.
- We sample at the Nyquist rate.
- We want our overall system to pass only the frequency content lower than 2000 Hz.
- We want the frequencies that we pass to be scaled by 1.

Which digital filter below correctly implements the system described?

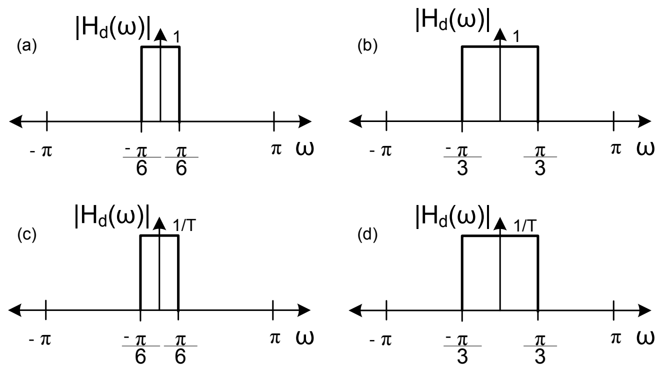

Fig. 3. Multiple-choice question based on misconceptions discovered during the course.

Because of the JiTT course structure, I was also able to construct the multiple-choice question in Figure 3 based on misconceptions that students possessed about how to scale the frequencies of the frequency response of a filter and how to scale the magnitude of the frequency response of a filter. Two of the filters inappropriately scale the magnitude by $1/T$ and two of the filters inappropriately scale the frequencies by an additional factor of 2. Because I was able to identify these misconceptions so early in the instruction cycle, I was able to specifically design more than six learning opportunities to counter the misconceptions and promote the correct conceptions before students' knowledge was tested on the final examination.

5. CONCLUSION AND LIMITATIONS

A JiTT based course enables and frees the instructor to focus on learning more about what their students know, so that they can tailor instruction and assignments to better match what their students need to hear. Implementation of such a course is time consuming and intensive, but the investment creates many new opportunities.

First, once the video lectures are developed and posted, the instructor may never need to lecture again. So while the initial course design requires a significant amount of time investment, instructors can reap the benefits of having more time to focus on developing other course material once the lecture material is set.

Second, a JiTT based course frees the instructor to interact with the students more than during a traditional lecture course. The instructor has more time to field students' questions, because there is no pressure to make sure that all of the topical content is covered in lecture that day. I also noticed a qualitative improvement in my students' readiness to ask and answer questions. I suspect that the students were more willing and ready to ask and answer questions because they had already had some time to digest the material.

Third, a JiTT based course frees the instructor to focus on diagnosing what the students know. This focus can allow the instructor to create more targeted ways to assess how well the instructional method is helping students to learn. Because instructors can diagnose what the students do not understand at multiple points, they can better follow how the students' level of understanding progresses. Because this teaching method allows the instructor to focus on discovering and potentially documenting common student mistakes and misconceptions, this teaching method can lead to greater documentation of these weaknesses in the literature. Ultimately, these documented weaknesses may provide new ways to assess what teaching methods and exercises help students learn specific course content and skills.

To facilitate interaction during problem solving sessions, JiTT was designed for courses that would be able to divide the students into smaller groups. Some of the JiTT teaching methods, such as problem solving sessions, will not scale up well for large classes. Nevertheless, most of the basic principles still work and can be used with large classes. Online exposure to content and students' submitted answers can still be used to get a baseline for how well students understand the material after watching the first lecture. An instructor for a large class probably will not experience the benefit of increased interaction with the students as much, but he will have a larger pool of student responses from online questions to better characterize what is truly difficult for the students to learn. An instructor for large courses would also need smaller discussion sections to facilitate problem solving sessions.

6. ACKNOWLEDGMENTS

Joe Handzik conducted the focus group discussions and transcribed the conversations. Mike Evans provided helpful tips for producing the video lectures. University of Illinois at Urbana-Champaign Provost's Initiative for Teaching Advancement and the College of Engineering provided seed money to help fund the start-up of this project.

7. REFERENCES

[1] David Paul Ausubel, *Educational Psychology: A Cognitive View*, Holt McDougal, 1978.

[2] M. K. Smith, W. B. Wood, W. K. Adams, C. Wieman, J. K. Knight, N. Guild, and T. T. Su, "Why peer discussion improves student performance on in-class concept questions," *Science*, vol. 323, pp. 122–124, 2009.

[3] D. Hestenes, M. Wells, and G. Swackhamer, "Force Concept Inventory," *The Physics Teacher*, vol. 30, pp. 141–158, 1992.

[4] J. P. Mestre, "Facts and myths about pedagogies of engagement in science learning," *Peer Review*, vol. 7, no. 2, pp. 24–27, Winter 2005.

[5] Catherine H. Crouch and Eric Mazur, "Peer instruction: Ten years of experience and results," *American Journal of Physics*, vol. 69, no. 9, pp. 970–977, September 2001.

[6] D. Evans et al., "Progress on concept inventory assessment tools," in *Proceedings of the 33rd ASEE/IEEE Frontiers in Education Conference*, Nov 2003, pp. T4G–1–T4G–8.

[7] K. E. Wage, J. R. Buck, T. B. Welch, and C. H. G. Wright, "The Signals and Systems Concept Inventory," in *Proceedings of the 2002 American Society for Engineering Education Annual Conference and Exposition*, Jun 2002, pp. 1–29.

[8] John R. Buck and Kathleen E. Wage, "Active and cooperative learning in signal processing courses," *IEEE Signal Processing Magazine*, vol. 48, no. 2, pp. 76–81, 2005.

[9] K. E. Wage, J. R. Buck, and M. A. Hjalmarson, "Analyzing misconceptions using the signals and systems concept inventory and student interviews," in *Proceedings of the 4th IEEE Signal Processing Education Workshop*, 2006, pp. 123–128.

[10] G. Novak, A. Gavrin, W. Christian, and E. Patterson, *Just-In-Time Teaching: Blending active learning with web technology*, Prentice Hall, 1999.

[11] K. A. Marrs and G. Novak, "Just-in-time teaching in biology: Creating an active learning classroom using the internet," *Cell Biology Education*, vol. 3, pp. 49–61, 2004.

[12] P. Chandler and J. Sweller, "The split-attention effect as a factor in the design of instruction," *British Journal of Educational Psychology*, vol. 62, pp. 233–246, 1992.

[13] S. Mousavi, R. Low, and J. Sweller, "Reducing cognitive load by mixing auditory and visual presentation modes," *Journal of Educational Psychology*, vol. 87, no. 2, pp. 319–334, 1995.

[14] M. C. Carlisle, "Using YouTube to enhance student class preparation in an introductory Java course," in *the Proceedings of the 41st ACM Technical Symposium on Computer Science Education*, Milwaukee, WI, March 2010, pp. 470–474.

[15] Geoffrey L. Herman, Lisa Kaczmarczyk, Michael C. Loui, and Craig Zilles, "Proof by incomplete enumeration and other logical misconceptions," in *ICER '08: Proceeding of the Fourth international Workshop on Computing Education Research*, Sydney, Australia, 2008, pp. 59–70, ACM.