A 21st Century Model for Disseminating Knowledge

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[joint work with Kevin Wayne]
A 21st Century Model for Disseminating Knowledge

- Mission accomplished?
- Disruptive changes
- Taking the plunge
- A way forward
- Postscript
<table>
<thead>
<tr>
<th>Category</th>
<th>When We Entered School</th>
<th>When We Started Work</th>
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<td>no textbooks for CS</td>
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*A more profound change than PCs or the internet.*
Fundamental challenge for teaching CS (1975-present)

has been to do without a *standard textbook* (the norm in other fields).
Central thesis (RS, 1975)

Most college students need a course in algorithms

The study of algorithms is a significant body of knowledge that is
- intellectually challenging
- pervasive in modern life
- critical to modern science and engineering

Anyone wanting to use a computer effectively needs to understand
- the scientific method in understanding program behavior
- how to compare algorithms and predict performance
- data abstraction
- classic data structures and types
- applying them to solve modern problems

Goal: A *textbook* for teaching algorithms to scientists, engineers and programmers.
Mission accomplished (2011)?

*Algorithms, Fourth Edition*

Classic text for decades, 750,000+ sold.
- “Algorithms with code”.
- Modern programming model.
- Model course in ACM–IEEE curriculum.
- Completely revamped each decade.
- Widely used around the world.
- Found throughout software infrastructure.

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<thead>
<tr>
<th>Edition</th>
<th>Goal for Code: Clear, Readable and</th>
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Problem: Many students are *not prepared* to learn much of the material.
Central thesis revised (RS, 1992)

All college students need courses in computer science

Computer science embraces a significant body of knowledge that is
- intellectually challenging
- pervasive in modern life
- critical to further study in most (if not all) academic disciplines

Anyone can learn the importance of
- modern programming models through data abstraction
- the scientific method in understanding program behavior
- algorithms and data structures
- abstract machines and their connections to real ones
- computation in a broad variety of applications
- preparing for a lifetime of engaging with computation

Goal: A standard intro text for CS that can stand alongside other standard intro texts.
[decades of difficult challenges omitted.]

- Identify content
- Change content
- Interface with the computer center
- Choose programming language
- Dot-com bust (enrolls way down)
- Change programming language
- Staffing
- Political battles
- Competing courses
- Inadequate resources
- Abandon computer center
- Financial crash (enrolls way up)
- Windows, OS X, Linux
- ...
**Computer Science: An Interdisciplinary Approach**

- 25 years in development.
- Fundamental ideas in the field for first-year students.
- Programming in Java through data abstraction.
- Theory of computation from Turing machines to intractability.
- Machine architecture and circuit design from gates to machine language.
- Turing, von Neumann, Boole, Shannon, . . .
- Stands with intro courses in economics, physics, biology, and other disciplines.
- Basis for Princeton’s most popular course.
- Model course in ACM–IEEE curriculum.

*Interdisciplinary* approach that embraces, leverages and supports other disciplines.
All in the context of applications

Ideal programming example/assignment

• teaches a basic CS concept
• solves an important problem
• is intellectually engaging and appealing
• is open-ended

```java
public class BouncingBall {
    public static void main(String[] args) {
        // Simulate the movement of a bouncing ball.
        double rx = .480, ry = .860;
        double vx = .015, vy = .023;
        double radius = .05;

        StdDraw.setXscale(-1.0, +1.0);
        StdDraw.setYscale(-1.0, +1.0);

        while(true) {
            // Update ball position and draw it there.
            if ((Math.abs(rx + vx) + radius > 1.0)) vx = -vx;
            if ((Math.abs(ry + vy) + radius > 1.0)) vy = -vy;

            rx = rx + vx;
            ry = ry + vy;

            StdDraw.clear();
            StdDraw.setPenColor(StdDraw.BLACK);
            StdDraw.filledCircle(rx, ry, radius);
            StdDraw.show(20);
        }
    }
}
```
2011: Time to declare victory?

**Goal:** A *standard intro text* for CS that can stand alongside other standard intro texts.

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**Introduction to CS enrollments**
- *Double* the height of the “bubble”
- 43% of all Princeton students.

---

"Almost done"

---

**“Algorithms” enrollments**
- *Three times* the height of the “bubble”
- 17% of all Princeton students.

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Little did we know what the future held...
A 21st Century Model for Disseminating Knowledge

- Mission accomplished?
- Disruptive changes
- Taking the plunge
- A way forward
- Postscript
Sit in your local coffee shop, and your laptop can tell you a lot. If you want deeper, more local knowledge, you will have to take the narrower path that leads between the lions and up the stairs.

The narrow path still leads, as it must, to crowded public rooms where the sunlight gleams on varnished tables, and knowledge is embodied in millions of dusty, crumbling, smelly, irreplaceable documents and books.
While Grafton’s reservations about putting knowledge online are well taken, I would also point out that there is quite a bit going on now in the academic world that doesn’t have much to do with old books. Indeed, as the author of many books, I wonder whether perhaps the book is not quite sacred as a means of disseminating knowledge.

What is the most effective way to produce and disseminate knowledge with today’s technology? How can we best structure what we know and learn so that students, researchers, and scholars of the future can best understand the work of today’s researchers and scholars?

I think that questions like these are more important and more difficult to address than whether we can put the contents of libraries on the Web.
Future of libraries?

20th century
• Students spend significant time in the library
• Faculty members depend on the library for research

21st century
• Students spend significant time online and have no need for the library
• Few faculty members in the sciences use the library at all for research

2020s?
• A few book museums (for Grafton)
• Digital library infrastructure (for everyone else)

How will we disseminate knowledge in the future? Will universities play a role?
Disruptive change II: Textbooks

We are on a road to ruin

- Prices continue to escalate.
- Students now *rent*, not own books.
- Planned obsolescence? Walled gardens?

Is there room for a good textbook? Will free web resources prevail?

No books!
Disruptive change III
2012: MOOCs go mainstream

Q. (Jan. 2012) Are you interested in teaching online?
RS+KW. No. (Too much work to do it properly.)

Q. (Apr. 2012) Trustees want it: we're doing it anyway. Are you in?
RS+KW. An offer we cannot refuse...

With apologies to our actual administrators

Andrew Ng and Daphne Koller

An online platform for the "course" abstraction

"Algorithms, Part I" (Summer 2012)

Immediate realization:
Our model is perfectly suited to go online.
[3 years of difficult challenges omitted.]

- Production design
- Record large lectures?
- Which presentation software?
- Developing assessments
- Can we do math this way?
- Who pays?
- Who owns it?
- “You’re just a troublemaker”
- Crashing the Amazon cloud
- Builds in the presentations
- Platform issues
- Lawyers and contracts
- ...

Brief summary of MOOC experience

Facts and figures
• Six courses produced, four already deployed.
• 70+ lectures, each running 60-90 minutes.
• 3000+ state-of-the-art lecture slides.
• Over 1 million people reached.

Distribution model is evolving (stay tuned)
• Intro courses offered as Coursera MOOCs.
• Advanced courses freely available (2017)
• Each course has an associated textbook.
• Lecture videos also bundled with the textbooks.
• Each textbook has associated web content.
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Sudden realization (2015)

Exactly how are we going to be teaching computer science at Princeton in the future?

RS: Hey, we have to use the studio-produced lectures!
Everyone else: Why would we change our biggest and best course?
[6 months of difficult negotiations omitted.]

- Students won’t watch
- Rules won’t permit it
- Will require preparation of new material
- Who will teach it
- How do we change videos?
- Video editing
- Who can watch them?
- Staff will need to reteach
- System won’t support it
- Too hard to set up
- ...
Glitches (not unusual)
- Over 90 degrees in the room.
- Biggest lecture hall on campus is too small.
- Students in aisles cannot see the screen.
- Sound system stops working halfway through.

Consequence. All students motivated to move online!
An unqualified success

Q. What do you think of the online lectures?

A. **82% of responses were positive.**

Students *loved* active participation in consuming lecture content
- “Prepares me for a lifetime of active learning online.”
- “I like this system, it really lets me go at my own pace and rewatch if I need to.”
- “The video lectures are **amazing**. I believe many classes would benefit from this.”

Course staff also reaped benefits
- No need to reteach lecture material in office hours.
- More time for interaction with students in small groups.
- More time for interaction in large class meetings.
- Scheduling complications virtually eliminated.
Time to declare victory?

Introduction to CS enrollments
- *Triple* the height of the “bubble”
- 2/3 of all Princeton students
- Largest course at Princeton

“Algorithms” enrollments
- *Four times* the height of the “bubble”.
- 40% of all Princeton students.
- 4th largest course at Princeton

Next challenge: Attain similar percentages among *all* college students.
A bonus: Scalability plus “CS for everyone” approach promotes *diversity* because everyone is prepared for further study in CS.

Bottom Line. Nearly 40% women majors, *more than twice* the national average.
A bump in the road

Growth at this scale is *unsustainable*
- By several measures, CS is 10% of the university.
- But only 5% of the faculty (!)

Three possible solutions (none likely).
- Double the size of the CS faculty.
- Double CS faculty salaries.
- Limit enrollments in CS.

Lesson: A new model that scales is an *imperative for continued success*.

Good news: The model can vastly extend our reach.
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Purpose of the university

is to produce and disseminate knowledge

Holy grail for research faculty
- Excellence in teaching.
- Devotion to research.
- Simultaneously.

A new model for teaching (this talk)
- Replace live lectures with online videos.
- Embrace technology for efficiency.
- Focus on student experience.
20th-century textbook model

was a standard for introductory courses (in the US) **and is still widely used**

**“20th century textbook” model**
- “Standard” textbooks emerge after significant investment by authors/publishers.
- Distribution model: Teachers “adopt” and students buy textbooks.
- Teachers prepare and deliver lectures (perhaps using author’s slides).
- Teachers assess, grade, and certify students.

**Pain points**
- Inefficiency of adjuncts/professors preparing and delivering “identical” lectures.
- Textbook publishing imploding after move to rental model.
- Passive lecture experience has become unsustainable.
- Assessment efforts generally do not scale.
21st-century textbook model

embraces technology to integrate four abstractions that are *here to stay*

“21st century textbook” model

- Authoritative **textbook** for use to *learn* and *study* the material.
- Studio-produced **video lectures** that *introduce* content and *inspire* more study.
- **Web content** for use to *explore* and *interact* with the material.
- **Web services** for use by teachers to *assess* and *certify* student learners.

**Benefits:** Consistent, scalable, and flexible support of *active* teaching/learning.
Abstraction 1: The "textbook"

has been an essential component in education for centuries and is *here to stay*

Well-understood since the Greeks.

Enabled for the masses by Gutenberg.

Still in widespread use.

Advantages

- Articulates what students can reasonably learn about a subject in a semester.
- Distills a lifetime of faculty experience for future generations.
- Provides a reference point for future studies related to the subject.

Challenges

- Books need to be written by increasingly busy research-oriented professors.
- Textbook publishing industry is imploding after move to rental model.
Abstraction 2: The “lecture”

has been an essential part of education for a millennium and is about to change

Advantages.
- Allows instructor to precisely control pace and direction.
- Stimulates development of a “community of scholars”.
- Encourages great teachers to inspire large groups of students.

Disadvantages
- Requires significant time and effort for preparation.
- Duplication of effort by instructors around the world.
- Places students in a passive role.
- Instructor must have effective skills for production and delivery.

Source: Office of Instructional Resources, University of Illinois-Urbana Champaign.

“Lecturing is that mysterious process by means of which the contents of the note-book of the professor are transferred ... to the note-book of the student without passing through the mind of either.”

— Edwin Emery Slosson

Is there a practical alternative?
Is there a practical alternative to traditional lectures?

20th Century

21st Century
Good news: Lecture presentation materials are evolving to new standard of excellence

Chalktalk

Overhead projection

"PowerPoints"

This is a horse.
Presentation elements example: Analytic Combinatorics

Mathematical derivations

- "Builds" control pace.
- Details to support reasoning are included.

"Story"

Drawings of combinatorial objects

Q. How many trees with $N$ nodes?
Good news: Studio-produced lectures embrace technology to provide consistent learning experiences for students.

Professional standards
- Production design
- Multiple cameras
- Video editing
- Presentation materials
- Recording sessions

By far the most time-consuming element: content creation
Good news: Online studio-produced lectures transform lectures from *passive* to *active* learning experiences for students

Students actively *choose their own pace*
- Typical beginners slow the pace at first.
- Typical advanced students view lectures at double speed.
- Everyone’s pace varies throughout the course.

Students actively choose the time and place they learn
- “Last thing in the evening, lying in bed.”
- “First thing in the morning, in the library.”
- “On the team bus.”
- “Sedgewick and chill.”

Lectures are always available for review
- Students review the material *until they understand it.*
- “Office hours” are dramatically reduced.
- Promotes diversity.
- Exam review is much less stressful.
Abstraction 3. "Web content" has exploded as essential in disseminating knowledge and is here to stay.

- No physical constraints.
- Available to everyone.
- Always up to date (dynamic).
- Content types not available in print.
Abstraction 4. "Web services"

are emerging as essential in education and are here to stay

Relevant widely-used web services
- Tools for creating documents, forms, blogs.
- Online forums supporting Q&A and discussions.
- Web-based testing and assessment tools.
- Platforms for video delivery.

20th century: All-encompassing locally-hosted “learning management systems”

21st century: Evolving suite of homegrown and “best in class” apps running in the cloud.
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• Mission accomplished?
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• A way forward
• Case in point
• Postscript
21st-century textbook model embraces technology to integrate four abstractions that are *here to stay*.

**“21st century textbook” model**

- Authoritative **textbook** for use to *learn* and *study* the material.
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Algorithms textbook

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- Completely revamped each decade.
- Widely used around the world.
Algorithms web content

http://algs4.cs.princeton.edu/

Developed by Kevin Wayne since the mid-2000s

- Fully integrated with the textbook
- Web presence.
- Landing and takeoff for search.
- Code, test data, animations.
- A living document.
- For use while coding, exploring.
- 10,000+ files.
- 1,000+ Java programs
- 6M+ page views in the past year
- 1M+ unique users in the past year
Algorithms online lecture videos

- Fully integrated with textbook
  - A “top 10 MOOC of all time”.
  - 24 lectures, about 1.5 hours each.
  - Also distributed by Pearson/InformIT.
  - Widely used around the world.
  - Have reached 1M+ people.
**Algorithms web services**

**Video delivery platform**
- Pearson
- Informit

**Program assessment infrastructure**
- File system/interface for student submissions.
- Dispatch mechanism to support human commentary.
- Used for many CS courses at Princeton.

**Forums and Q&A**
- Piazza

**Automated program testing (stay tuned)**
- Extensive fine-grained automated testing.
- Correctness (of course).
- Sophisticated performance and probabilistic tests.
- Deployed in an AWS docker container.

**Quizzes and exams (stay tuned)**
- Random questions drawn from templates.
- Hundreds of templates; millions of questions.
- Auto-graded for self-assessment.
- Web service in a cloud server.
Example 1: Combinatorial questions

A. __________ Every problem in NP is also in P.

B. __________ There is a DFA that can recognize all binary palindromes.

C. __________ There is a Turing machine that can decide whether the number of 1s on its input tape is prime.

D. __________ No polynomial-time algorithm can solve the Halting Problem.

E. __________ If P = NP there is a polynomial-time factoring algorithm.

8. Computability/Intractability (5 points). For each of the computational problems below, indicate its difficulty by writing the most appropriate choice of T (true), F (false), or ? (nobody knows) in the blank at left.

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\[
\binom{50}{5} = 2M+ \text{ questions}
\]
Example 2: Data-driven questions

Q17. String sorts. The column on the left is an array of strings to be sorted. The column on the right is in sorted order. The other columns are the contents of the array at some intermediate step during one of the algorithms below. Write the letter corresponding to the correct algorithm under the corresponding column. You will need to use some letters more than once. 

\[ \text{Hint: Do not trace code—think about algorithm invariants.} \]

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A. input  B. LSD radix sort  C. MSD radix sort  D. 3-way radix quicksort (no shuffle)  E. sorted result

\[ 26^5 \times 24! = 7371780749591669477065359360000 \text{ questions} \]
Algorithms automated assessments: quizzes and exams can be generated and graded in a fully automatic fashion.

https://demo.quizzera.io/

Typical applications
• Self-assessments in a large flipped class.
• Generate huge database of questions for a MOOC.
• Easy to adapt for use in a fully online class.

Quality and consistency of assessments are dramatically improved via technology.
Algorithms automated assessments: programs can be subjected to extensive fine-grained tests and graded automatically.

Programs are first checked with best-in-class tools
- Every program must compile.
- Style checks help develop best-practice programming habits.
- Automatic bug-finding is essential (“because it’s easy”).

All assignments are based on a fully specified API, enabling
- Correctness checks (input-output pairs).
- Timing tests (essential in an algorithms course).
- Memory utilization (also essential in an algorithms course).
- Probabilistic testing (for randomized inputs or algorithms.)

Typical applications
- Grading programs in a large flipped class.
- Grading programs in a MOOC.
- Easy to adapt for use in an online class.

Quality and consistency of assessments are dramatically improved via technology.
IF YOU DON'T TURN IN AT LEAST ONE HOMEWORK ASSIGNMENT, YOU'LL FAIL THIS CLASS.

YEAH. BUT IF I CAN FAIL THIS CLASS, THE GRADES ON MY REPORT CARD WILL BE IN ALPHABETICAL ORDER!

https://xkcd.com/336/
Bootstrapping

Courses produce large numbers of qualified students—why not put them to work?

**Not-peer grading**

- Feedback on code quality is *essential* for beginning programmers.
- Recruit students who have done well in the course to provide it. (they are *not peers*—they have another year of experience coding.
- They can also provide *grades* to supplement automated process.
- Graders expand and reinforce their knowledge by doing so.

**Software development**

- Best students are *strongly motivated* to create a killer app.
- They also seek independent research projects.
- They also understand the shortcomings of existing software.
- *Put them to work!*
- Resulting software tends to be *far better* than otherwise available.
New in 2016: Computer Science

Computer Science
- Web content under development since 2000. 2M+ unique users and 8M+ page views in the past year.

Also available: Analysis of Algorithms and Analytic Combinatorics (free).
Also available: AofA and Analytic Combinatorics

Textbooks

Online course materials

Freely available
  • Weekly assignments
  • Lecture videos
  • Lecture slides
  • Q&A

Not a MOOC

http://ac.cs.princeton.edu/online
Using a 21st century textbook at a brick-and-mortar institution

Books and online content are 21st century resources. Audience: Anyone wanting to teach or learn CS.

20th century

- Students read textbook.
- Professor delivers large lectures.
- Teaching assistants lead small classes.
- Professor + TAs develop assignments.
- Professor + TAs hold office hours.

21st century

- Students read textbook and watch online lectures.
- Teachers lead small classes based on online content.
- Teachers develop assignments using online content.
- Teachers hold class meetings and monitor forums.

Benefits

- Consistent product even in huge class with many faculty.
- Students experience modern studio-produced lectures on their own time.
- Teachers have time to focus on helping students succeed.
A paradox

Use of online lectures *enhances* personal interaction between faculty and students.

Online videos are more personal than one might think!
- Each student spends significant time with RS.
- RS gets e-mails, waves, smiles and selfies around the world.

**Examples of interactions enabled by the model**

- Professor, students and TAs meet periodically in sections.
- More frequent exams, with preparation and review sessions.
- Discussion of student-proposed *exam questions*.
- Large *class meetings* about “fun” topics.

**Quality** of interaction is better than with live lectures.
- Nobody is taking notes.
- Interactions are about connecting and applying ideas.
- Teachers are free to explore, knowing that basics are covered.

*We focus on outcomes, and we care about student experiences. If we were to try to cover more material in the class meetings or try to do more of our interaction in large groups, the experience would suffer.*

– David August, in response to a parent complaint
Mission accomplished?

Textbooks

Analytic Combinatorics

Computer Science

Algorithms

Studio-produced lectures

Online content
A 21st Century Model for Disseminating Knowledge

• Mission accomplished?
• Disruptive changes
• Taking the plunge
• A way forward
• Postscript
Questions answered (faculty)

Q. Isn't developing an online course time-consuming and difficult?
A. Yes! 50-100 hours of preparation per lecture.
A. Yes! My workflow requires skill in Unix, emacs, Mac OS X, Dropbox, Illustrator, InDesign, Java, C, TeX, video capture, KeyNote, Acrobat, HTML, MathJax, Mathematica, PostScript, and a dozen other tools I can't even name.
A. It's less time-consuming than writing a book.

Q. I think my administration will fire me and use your lectures.
A. I'm wondering about that myself!
A. Cut costs by firing teachers? I think not.
A. Your students need you to help them succeed and certify that they did so.
A. Does it make sense for hundreds of professors around the world to be preparing and delivering lectures on Quicksort, hashing, and a dozen other topics every semester?
A. Are you planning to spend 50-100 hours of prep time?
A. Your students are already watching my lectures.
### Questions Answered (Administrators)

#### Q. Why aren't more faculty developing online courses?
A. It's difficult! And you are evaluating them on research, not this.

#### Q. Please do a scientific study on online vs. traditional lectures.
A. Sure. Please provide the % of students attending traditional.
   (I know the answer for online.)
A. Did you do a study when your faculty switched to PowerPoints?

<table>
<thead>
<tr>
<th>Q. What can we do to improve things?</th>
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<tbody>
<tr>
<td><strong>A. Embrace technology.</strong></td>
</tr>
<tr>
<td>A. Develop a <em>teaching class</em> of professors who can teach blended classes.</td>
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<tr>
<td>A. Provide support and real incentives for teaching and content creation.</td>
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<tr>
<td>A. Invest in <em>research</em> at the interface of education and technology.</td>
</tr>
<tr>
<td>A. Attract and provide resources to the best and brightest professors in the field.</td>
</tr>
<tr>
<td>A. Develop <em>academic leadership</em> for charting the future.</td>
</tr>
</tbody>
</table>

#### Q. How much will it cost our institution to embrace online education?
A. Less than you are spending on many things that are less central to your mission.
   
   **A. You need to plan to invest in this at the scale you are investing in the library.**
A. Can you afford to *not* embrace online education?
A parting thought
(from John Hennessy in an interview for an article by Ken Auletta the New Yorker, 2012)

“[Universities,] like newspapers and music companies and much of traditional media a little more than a decade ago are sailing in seemingly placid waters.”

“But ... there’s a tsunami coming.”
What happened to the tsunami?

*I think the bloom is now off the rose, and now is going to be the time when some really hard-nosed thinking has to be done about the true value of these online courses.*

Shirley Tilghman, 2013

Stumbling blocks
- *Institutions* are trying to take control (and failing).
- Content creation is the province of *individuals*.
- Bad business models, created prematurely.
Result: Plenty of lost opportunities.

RS: Looks like a tsunami to me!
- Tens of thousands of pages of online content
- 100+ hours of lecture videos.
- Reaching millions of individuals.
- 1990s: Lucky to be able to teach my own children.
- 2030s: Will be teaching my own *grandchildren*. 
A 21st Century Model for Disseminating Knowledge

Robert Sedgewick
Princeton University

[ joint work with Kevin Wayne ]