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The inverted classroom in introductory calculus: Best practices and potential benefits for the preparation of engineers

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The inverted classroom in introductory calculus: Best practices and potential benefits for the preparation of engineers

What is the inverted classroom?

Higher education has for many years organized its curricula and instruction around an instructional design model that should be instantly recognizable to most readers. This model involves three phases for each unit that is taught:

1. The instructor decides what concepts and topics should be covered in the unit and articulates a collection of learning objectives that will eventually be assessed.

2. The instructor uses class time to present information on the main concepts and topics of the unit to students, usually through lecture.

3. Students work outside of class on activities intended to internalize the content they received in class and thereby attain (over time) mastery of the learning objectives.

In other words, class time is used to present or transfer information from the instructor to the student, and out-of-class time is used to assimilate and master that information.

We will call this model the *traditional classroom* because of its predominance in higher education. The traditional classroom is not only familiar to most college and university students and graduates, it is perhaps the only model many have ever encountered. In fact, the traditional classroom is so familiar that it may be difficult to imagine a course being designed any other way and difficult to think about the possible drawbacks of the traditional classroom that could be addressed by a different design.

However, alternative designs are possible. One such alternative is the *inverted* or "*flipped*" classroom model. The inverted classroom model also involves three phases, but those phases are noticeably different from those of the traditional model. For each unit taught:

1. The instructor decides what concepts and topics should be covered in the unit and articulates a collection of learning objectives that will eventually be assessed.

2. Students are given a structured out-of-class assignment in which they encounter and learn independently about the basic concepts and information for the unit, through a combination of text documents, recorded lectures, interactive exercises, and other means.

3. Class time is used to assess students' basic knowledge (gained in the pre-class exercises) and work on challenging sense-making activities designed to assimilate the basic information.

The concept of the inverted classroom in higher education can be traced back to a paper by Lage, Platt, and Treglia[1] describing its use in teaching university-level economics. The inverted classroom gets its name because it "flips" the second and third phases of the traditional model. Information transfer is relocated from class time to out-of-class time, and assimilation-oriented activities that might have been homework in the traditional model are now the centerpiece of class activities in the inverted model using the time that is freed up by relocating information transfer tasks.

What problems does the inverted classroom solve?

Despite its status as "traditional", the traditional classroom has three design issues that are addressed by the inverted classroom.

First, in the traditional classroom, *the difficulty of student work is inversely proportional to the accessibility they have to the instructor*. In terms of Bloom's Taxonomy[2], information transfer tasks (such as taking notes from a lecture) typically address only the bottom levels of cognitive tasks (*remembering*, *understanding*, *applying*). In the traditional classroom, the instructor is fully present during these tasks and is in fact the centerpiece of these tasks. On the other hand, student out-of-class work is typically aimed at the more difficult tasks of analyzing, evaluating, and creating, during which time the instructor is not physically present and may in fact be inaccessible at the point of highest need. By contrast, in the inverted classroom, students work on the simplest tasks (information transfer) while the instructor is not physically present and the most complex tasks when the instructor is present, making task difficulty *directly* proportional to accessibility to expert guidance.

Second, in the traditional classroom, *students have little control over the stream of information that is being transferred*. The traditional classroom typically features a "live" lecture as the main activity of class time, and the students' job during class is to copy and organize the information from the lecture in real time. Organizing information in this way can be a valuable activity, but the format in which it takes place in a live lecture can be problematic for some students. Students with certain learning disabilities, for example, struggle to attend to a live stream of information. The task of organizing information from a stream is made simpler for learners by having the ability to pause and replay that stream as needed and by having the option to access and view content at times, in quantities, and in locations of their choosing. By recording instructor lectures to video and putting them online for student access, this issue is directly addressed by the inverted classroom.

Third, *traditional classrooms do not typically provide explicit instruction on skills students need for lifelong learning*. Those skills include the ability to identify when one's personal knowledge runs short and when to seek out more information, the ability to comprehend new information independently when it is sought out, and the ability to monitor one's own progression through the process of learning new content. These skills are often left up to the student to learn through unguided experience. In the inverted classroom, by contrast, students can get regular and explicit practice in these and other skills and opportunities to put them into practice as part of the everyday workflow of the course.

Theoretical framework: Self-Regulated Learning

A theoretical framework for understanding and motivating the inverted classroom is the concept of *self-regulated learning* as developed by educational psychologist Paul Pintrich[3]. The self-regulated learning (SRL) framework operates under four assumptions:

1. Learners are considered to be active participants in the learning process and construct their own meanings, goals, and strategies for learning from their learning environment and from their pre-existing knowledge.

2. Learners have the potential to monitor and regulate aspects of their learning and learning-related behaviors as well as some features of their environments.

3. Learners have some kind of goal or standard against which they can compare their learning processes, so that they can make realistic decisions about whether their learning processes are adequate for a given task or whether changes should be made.

4. Learners use self-regulating activities as mediators between their personal characteristics and their actual performance. That is, the learning that self-regulating learners experience is not merely a consequence of their environments, personalities, demographic status, or other personal or contextual factors, but rather is the result of learners using well-chosen activities to mediate the relationships between these factors and their achievement.

The SRL framework agrees with the concept of "lifelong learning" as it is frequently formulated. When we say that we want students to be lifelong learners, in other words, what we mean in large part is that we wish for them to become self-regulating. Successful lifelong learners demonstrate the ability to sense when they need to learn (or to learn more) about a concept, are able to seek out and digest new information independently while knowing when and how to ask others for input, can judge for themselves whether they are learning well enough and when to make changes, and can mitigate personal or environmental factors in learning through self-regulating activities.

Self-regulated learning is both the main feature and the main goal of the inverted classroom. By making them responsible for acquiring basic fluency in new material, students are asked – in *every instructional unit* – to learn independently, to compare their understanding of what they have learned to explicit learning goals and decide whether their learning is sufficient, to seek out additional sources of information and practice if their learning is insufficient, and ultimately to construct a model of new content based on those choices. Pre-class assignments in the inverted classroom can be designed so that explicit instruction on self-regulation activities can be provided.

The Engineer of 2020 and the inverted classroom

The issue of self-regulated learning comes to a particularly clear point in the seminal document *The Engineer of 2020*[4] and its vision for engineering and engineering education in the twenty-first century. While this document is not a theoretical framework, this document is quite explicit as a practical framework about the role of self-regulated learning in the education of engineers in the current century:

> Given the uncertain and changing character of the world in which 2020 engineers will work, engineers will need something that cannot be described in a single word. In involves **dynamism**, **agility**, **resilience**, and **flexibility**. […] Encompassed in this theme is the imperative for engineers to be **lifelong learners**. They will need this not only because technology will change quickly but also because the career trajectories of engineers will take on many more directions – directions that include different parts of the world and different types of challenges and that engage different types of people and objectives. Hence, to be individually/personally successful, the engineer of 2020 will learn continuously throughout his or her career, not just about engineering but also about history, politics, business, and so forth. [*Emphasis in original*]

The attributes emphasized here accord with and contain the notion of lifelong learning, which in turn agrees with the basic notions of self-regulated learning. Indeed, a self-regulating learner exhibits “dynamism”, “agility”, “resilience”, and “flexibility” not only in his or her areas of expertise but in all areas of learning and even in the process of learning itself.

Eventually we must ask not only what pedagogical methods best enable students to reach the lofty goals of *The Engineer of 2020* and what curricula provide the best platform for their work, but also we must ask what instructional design model is best suited for student work. While students can attain these goals in both the traditional and inverted classroom models, the inverted model seems to be more explicitly in line with the kind of work students must do in order to attain them.

An inverted Calculus 1 course: Course background

Having set up a general description of the inverted classroom model and a theoretical framework that supports its suitability for modern engineering education, we now focus on a particular case study involving the education of engineers. This case study is about a Calculus 1 course – a foundational course for all engineers – designed and taught at the author's university, a large regional university in the Midwestern United States during Fall semester 2013.

The university currently enrolls 24,477 students in both undergraduate and graduate programs, including 921 students studying engineering. In Fall 2013, the university ran 14 sections of Calculus 1 with a total enrollment of 402 students. Of these, 149 (37%) had declared a major in engineering. During the summer of 2013, a colleague of mine and I began to discuss the possibility of teaching our sections of this course using an inverted design. This discussion emerged from a dissatisfaction with teaching the same course during the summer in a traditional format. Student performance on assessments in that course was acceptable, but the course lacked time and space in class for exploration of difficult concepts due to the predominance of lecture. Having taught several courses in the past using an inverted model[5,6], the time seemed right to move calculus toward this model as well.

Instructional design and course construction

The redesign of Calculus 1 involved four major components.

First, the course objectives were realigned so that self-regulated learning was a priority in the course. The major course objectives in the official departmental syllabus were unchanged; for example, student fluency in performing various calculus-related computations was still a high priority. But some language was added, or altered from existing objectives, to stress the development of self-regulated learning, for example:

- *Use a variety of computing technologies effectively to identify patterns, make deductions, visualize information, solve problems and communicate results of one's work.*

- *Exhibit the ability to acquire basic knowledge of a new concept on one's own through reading and other media.*

- *Exhibit the ability to map basic concepts in calculus onto newer (harder) problems.*

Second, we sought out a textbook for the course that would be suitable for the philosophy and practice of an inverted classroom. Such a textbook would be structured so that students could, and should, read it for comprehension prior to class and should support the vision of lifelong/self-regulated learning.

Many textbooks, including many standard ones, did not make the cut due to an excessive emphasis on esoteric algebraic computation, a confusing design or layout, or a failure of congruence between the new course goals and the textbook's goals. In the end, the textbook *Active Calculus* by Matt Boelkins was selected[7]. This textbook enjoys at least three points in its favor. First, it is designed specifically for initial use prior to class through the use of "Preview Activities" that students are to work before any other reading takes place. Second, examples in the text are sparse. Some may view this as a "bug", but we viewed it as a feature that allowed us to give students direct practice on constructing and checking their own examples. Third, and significantly, the book is freely available online as a PDF, which accords with our beliefs about minimizing the financial burden on students.

The third design component was the creation of a series of videos to replace in-class lectures. The production of the videos was guided by four unifying principles:

1. The videos should be relatively short, between 5 and 8 minutes in length.

2. The videos should not duplicate the material in the textbook but rather supplement it, primarily through worked-out examples and discussions that help students make sense of concepts.

3. The videos should provide perspective on a process or concept that students would not generate on their own. They should discuss explicitly the mental processes used by a professional mathematician in solving a problem, issues of self-regulated learning (such as how to determine for oneself whether an answer is correct), and connections from the topic at hand to topics elsewhere in the course. The videos should *not* merely be step-by-step "how to" guides that tell a student what to do without understanding.

4. The videos should be of high quality, using high definition video and professional-quality audio.

A list of topics for videos that encompassed the entire Calculus 1 sections of *Active Calculus* was drawn up in early summer 2013, and the labor of production was divided between the two instructors. Most of the videos were produced in a two-week period in early August 2013 and then completed on a rolling basis, with the last video uploaded in early November. The complete playlist, consisting of 91 videos and over 9 hours of content, is available on YouTube at [*web link; redacted for blind review*]. The videos are licensed under a Creative Commons Attribution 2.0 Generic license (http://creativecommons.org/licenses/by/2.0/) which allows anyone to use or remix the video content provided they give attribution to the original authors.

The videos were created using a combination of tools. For the author's videos, one of two methods was used. For videos that are primarily lecture slides with a voice-over, the slides were created using the Beamer package in LaTeX. A script was written beforehand and read aloud using the free software Audacity to record the audio. Then the slides were played back while the voice-over audio was running, and the screencasting software Camtasia was used to record the slide presentation. For videos that focused more on examples worked out by hand, the software Doceri was used to set up a blank template for writing and then mirrored to the screen of a computer; the example was worked out by hand on the iPad screen and the voice-over recorded live during the process, with both audio and video captured using Camtasia. The resulting video was then uploaded to YouTube. Videos done by my collaborator were recorded using the web-based tool Screencast-O-Matic and uploaded to YouTube.

The final design component was the creation of in-class activities that emphasized collaborative student work on challenging problems and on making sense of concepts. Some of these were modified from activities found in the *Active Calculus* textbook. Others were adapted from homework assignments given in previous incarnations of the course that used a traditional model, while others were newly-created. All activities focused on collaborative work on difficult problems, some with technology and some without, and with an emphasis on building self-regulated learning skills such as checking one's work with technology, self-activation of prior knowledge, and so on. Links to two such activities are included in the Appendix.

Implementation

With the basic materials and instructional objectives in place, the Calculus course was ready to be implemented. Each instructional unit in the course involved student activity in three distinct phases: pre-class work, in-class work, and post-class work.

The inverted classroom emphasizes students gaining basic fluency with new concepts prior to class. However, many students in the course had neither training nor experience in guiding their own learning in an independent, pre-class environment. Therefore a highly structured, goal-oriented pre-class activity was crucial to ensure that the in-class work could be done successfully. The model used in this class was an recurring assignment called *Guided Practice*.

Every new instructional unit was introduced with a Guided Practice document. Links to sample Guided Practices have been included in the Appendix. Each Guided Practice consisted of the following parts:

1. An overview giving the main highlights of the new unit and its connections with previous units.

2. Two lists of learning objectives to provide students with a standard against which they could judge their progress in mastering the unit. The lists were labelled "Basic" and "Advanced". Students were responsible for mastering the Basic objectives prior to class; the Advanced objectives were to be mastered with further practice and essentially set the agenda for the class meetings.

3. A list of print and video resources to use in getting basic information about the concepts in the unit. This typically consisted of a section of the textbook to read and a list of links to YouTube videos. Occasionally, supplemental print and video was included for students to read and watch on an optional basis (for example, a video from a trigonometry class reviewing inverse trigonometric functions).

4. A series of exercises that gave students a basis for evaluating their understanding of the content against the learning objectives and for providing the instructor with evidence that the student has attained fluency in the basic learning objectives.

For example, in the example Guided Practice in the Appendix, one of the basic learning objectives is to "Use the limit definition of the derivative of f to find a formula for f' if f is a constant, linear, or quadratic function." This is an unambiguous, action-verb-delineated learning objective whose attainment can be measured simply by trying a problem and seeing if the solution is correct. Then, this is followed up by an exercise in which students are asked to use the limit definition of the derivative to take the derivative of $f(x) = 3x^2 - 1$.

Guided Practice was assessed on a scale of 0 to 2 on the basis of completeness and effort only. That is, students were not penalized for mathematical or conceptual mistakes – only for failure to give a good-faith effort to complete the assignment. Students submitted their work online using a Google form; the submissions on the Google form were read an hour before class, and if any major misconceptions arose, those were put onto the agenda for the class meeting for the day.

Upon arrival to class, students were allowed 5 to 10 minutes at the beginning to ask questions on the reading and viewing. Students also had the opportunity to raise questions in the Guided Practice assignment, and if no questions were raised verbally in class, the time was spent reviewing the questions submitted online and any misconceptions that needed to be addressed from the Guided Practice work. Following the question/answer time, students took a three-question Entrance Quiz that covered the basic learning objectives. Quizzes were administered on paper and collected after three minutes of work. After collecting the students' work, the quiz was immediately debriefed at the board and document camera so that students received instant feedback.

Following the Q&A time and the Entrance Quiz, the class was typically left with about 30 minutes to work on class activities. As described above, these activities were often taken from the Activities in the *Active Calculus* book and modified to fit the particular needs of the audience. Most were on the cognitive level of homework that would be assigned for out-of-class work in a traditional setting. Students were allowed and encouraged to work in groups. During the in-class activity time, the instructors had the ability to check in with every student at least once, and quite frequently students would move around to consult with other groups on their progress or go to the board to instruct each other or another group. Without the controlling influence of a live lecture present, the liberated time in class was used actively and robustly.

Finally, once class time was completed, students typically would have three items to work on outside of class. First, students worked the Guided Practice for the next unit. Second, the online homework system WeBWorK was used to provide mechanical practice for students outside of class; typically students were to complete about 10 WeBWorK questions per week and were allowed unlimited numbers of attempts on each problem until the deadline. Third, students worked on a problem portfolio that consisted of several difficult calculus problems. Over the course of the semester, students chose problems to work from a list, submitted and received feedback on initial drafts of their work, and submitted final drafts of their work written up using mathematical typesetting software. Portfolio problems were assessed on the basis of a combination of mathematical and written quality.

Class management

In practice, managing the student experience in the inverted Calculus course came down to three imperatives: ensuring students arrived at class adequately prepared for class activities, helping students work productively in a collaborative setting during class, and helping students navigate the expectations and everyday workflow of an inverted class.

The goal of ensuring that students come to class adequately prepared is often phrased as "making sure students do the reading (or viewing)". But in fact, we imposed no requirement that students *had* to complete all the reading or all the viewing – or even any of it. Instead, the pre-class work was designed so that students would *want* to complete it. By separating the Basic learning objectives from the Advanced objectives and requiring pre-class fluency with only the Basic objectives, students had a clear idea of what they needed to learn and were not overwhelmed by the (false) expectation that they needed to learn *everything* prior to class. By giving them accessible and professional-quality print and video resources as well as short list of exercises that targeted the Basic objectives explicitly, students could learn the content on their own and get clear self-generated feedback on their understanding. By grading only on the basis of completeness and effort, students were encouraged to try their best and not worry about making mistakes. (Indeed, the initial mistakes made by students provide crucial information for planning the in-class activities.)

Did students actually do the pre-class assignments, and if they did, did they successfully attain fluency on the content? One means of determining the answers to these questions is to look at student scores on Guided Practice and Entrance Quizzes. In the author's two sections, each of which enrolled 30 students, there were 25 Entrance Quizzes given for a total of 75 points in all. Those two sections attained median totals on the Entrance Quizzes of 58.5 and 54.0 with standard deviations of 8.31 and 11.33 respectively. Those correspond to averages of 78% and 72% respectively on Entrance Quizzes. The relatively high standard deviations indicate a wide variety in those scores, however, as might be expected among freshman-level courses. On the other hand, out of 48 total points given through Guided Practice during the semester, the author's two sections attained median totals of 44 and 46, indicating that nearly all students were completing the Guided Practice every time. These data indicate that the great majority of students were completing the pre-class assignments and attaining a modest level of fluency on the content, which is precisely what we intend with pre-class work.

To help students maintain productivity while working collaboratively in class, we found that the key is simply to check in frequently with each student and working group and observe their progress. Thanks to the amount of in-class time freed up by relocating lectures, it was possible to check in with every student in every class meeting as they worked on in-class activities. Through frequent personal interaction with the groups and individuals, individual needs could be gauged and personalized side work could be assigned in the moment. For example, a student struggling with the concept of function composition during a class period on the Chain Rule could be assigned a "spot" activity on this concept alone, or given an additional video to watch while others worked.

The final class management imperative is to help students acclimate to daily work in an inverted class. This acclimation process typically involved two main issues. First, the inverted class involves a great deal of time and task management due to the amount of tasks done outside of class, and many students lacked experience with this management. The solution to this issue was simply to talk explicitly about basic task management skills, such as using a calendar to record due dates for assignments and developing the habit of checking email and discussion boards repeatedly throughout the day.

The second and more troublesome issue was that many students, perhaps due to their long association with the traditional classroom, expect class time to be focused on information transfer and feel disoriented, even defrauded, if class time is spent in some other way. Some students felt that they were being asked to teach themselves calculus and that they were not able to ask questions while viewing the course lectures online. Of the students who felt this way, many could be helped by pointing out that higher education focuses not on information transfer but on developing self-regulated skills; that employers of engineers value self-regulated learning skills at least as much as content mastery; and that in any event, multiple channels for receiving help at any time existed in the course and the quality and quantity of help would be greater than what they experienced in a traditional setting.

These are sensitive issues, but in the inverted classroom they are at least openly discussed, and this tends to produce a healthier overall relationship between the student and the instructor if the students' concerns are handled seriously and with grace.

Time and work requirements for instructors

To convert Calculus 1 from a traditional to an inverted design model did take considerable time and effort. Instructors who are considering the inverted classroom should not labor under the illusion that it will be less work. However, the benefit was worth the expense on three different levels.

First, the time spent creating the course materials (especially course videos) was considerable, but it is a one-time expense that need not be replicated in future course offerings. We estimate that approximately 70 hours were spent making the 9+ hours of course video, split between two instructors. However, the next time the course is offered, the videos are already completed and curated, and except for additional videos and corrections of mistakes in existing videos, this work need never be done again. Moreover, the videos are freely available for anyone to use, and so another instructor can use the videos wholesale with no effort at all expended.

Second, by relocating the lecture content to an online repository, the preparation time for classes shifted focus from content creation to the design of learning activities. The latter does not necessarily take less time than the former, but in our experience the work of creating effective learning activities is more interesting and more focused on student learning than writing lecture notes. And in many cases, writing activities *did* take less time – especially if one is updating activities made for previous course offerings.

Third, student engagement with the course was noticeably greater in the inverted design, as will be documented in the next section. This reason alone, for us, made the redesign worth the effort.

Results

In the initial offering of the inverted Calculus 1 course, instructors gathered qualitative data in the form of student responses to writing prompts about their experiences in the class. Students were asked on several occasions to voice those opinions. One student wrote:

> The setup for the class is perfect, i dont [*sic*] understand why all classes are not like this, like you said the hardest part of the class is the homework and other teachers expect us to just pick up from what they said in lectures which is out of date teaching. Like for my Engineering class we do all the hard stuff outside of class. Homework for example, we type code to run a program and we are supposed to read our chapters to figure out how to do it but i can not ask questions when i need answers, i have to wait a day or a couple days for office hours for help and it seems like everyone has an issue and the teacher is overwhelmed and the teacher uses the same teaching methods year after year and they see the success rating is always down. I feel all class [*sic*] should do the style of learning we do in your class.

Another writes:

> The "flipped" format of this class is definitely helping me with tackling the tougher challenges in class. Watching the lectures is very beneficial and I really enjoy those as I can stop them at any point and think about what is being said and write down formulas and whatnot.

And another writes:

> I really enjoy this style of class. I would like to take one similar to this for my calc 2 experience. Are there any other professors that run class this way? If so I would love to know as I would switch into a class like this in a heartbeat.

While some students were initially somewhat apprehensive about the use of the inverted classroom, most of those students warmed to the idea after seeing its effectiveness in practice. Only on a few occasions did students voice dissatisfaction with the course design. When dissatisfaction was expressed, student concerns tended to focus either on comfort level (a sense that the student would feel more at ease if the professor would lecture in class) or on personal convictions about how higher education should be structured (that the professor's job is to lecture and the student's to take tests that come directly from those lectures). Neither source of dissatisfaction is based on the students' actual learning experiences or progress toward attainment of learning objectives in the class, and in fact most of these concerns dissolved when students were shown how much they were learning and how well they were preparing themselves for future learning experiences.

Future work

The case study described above was an initial offering of an inverted Calculus 1 course, and as such it is intended as a proof of concept. The results of this initial offering are promising. The course increased student engagement with Calculus, addressed key issues in self-regulated learning attendant with a liberal education and with the expectations of *The Engineer of 2020*, and provided students with a high degree of challenge along with a high degree of support.

The next step in studying the inverted classroom in this setting is to test it on a larger scale and collect quantitative data as well as qualitative. A large-scale study similar to Hake's classic "interactive engagement" study in elementary physics courses[8] would be well suited for examining the inverted classroom in calculus, using instruments such as the Calculus Concept Inventory in pre- and post-testing environments. Research could also be done examining the relationship between the inverted classroom design and student gains on measures of self-regulated learning, such as the Motivated Strategies for Learning Questionnaire[9] and various metacognitive inventories.

We would not expect significant results in either mathematical or SRL skills merely by flipping the contexts of lecture and homework; rather, such significance would seem to depend on the design of course assignments for both pre- and in-class work. A multitude of research questions then becomes apparent. For example: How should pre-class activities be structured in order to maximize student learning during independent reading or viewing? How should online lectures be structured to best support student learning before class? Is it more effective to have a combination of print and video sources versus only print or only video? Does the inverted class design help, or hurt, students with learning disabilities, students whose first language is not the language used in the videos, and others for whom attending to an information stream is problematic?

In sum, the inverted classroom provides a design platform on which effective pedagogy can run. Given that platform, a wide variety of future research is available to determine how best to employ that pedagogy to a diverse range of students.

Appendix: Sample Materials

Below are links to sample activities used in the case study described in the paper:

- Sample guided practice for unit on related rates problems: [*Link redacted for blind review*]

- Sample in-class activity for unit on related rates problems: [*Link redacted for blind review*], PDF

- Sample guided practice for unit on the definite integral: [*Link redacted for blind review*]

- Sample in-class activity for unit on the definite integral: [*Link redacted for blind review*], PDF

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