Development of an Advanced Course in Computer-Aided Design, Analysis and Prototyping

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Introduction

The increasing power of CAD has had a significant impact on the product development process, allowing improved quality, reduced cost products to get to market faster. Mechanical CAD (MCAD) software is rapidly evolving into what might be better described as product development, or perhaps virtual prototyping software. MCAD is increasingly integrated with analysis and simulation tools; upfront, predictive engineering is a reality in many companies. Surface modeling tools traditionally employed by industrial designers are now available in mid-range CAD packages. Low cost 3D printers are increasingly common. MCAD collaboration tools are used to improve communications within the product development team.

How might engineering educators capitalize on these exciting trends? One possibility is to employ associatively linked modeling, analysis, and prototyping tools in a dedicated course; another more ambitious possibility is to make the concerted effort to use these same tools across several design and analysis courses. The latter approach offers the potential of a more tightly integrated curriculum; instructors would develop a better understanding and awareness of what goes on in related courses; communications and coordination among faculty would improve. In addition, students would leave with four years of solid experience using CAD/CAM/CAE software.

This paper describes a new course, *Computer-Aided Design Analysis and Prototyping*, offered for the first time in the Spring 2003 semester, by the Department of General Engineering (GE) at the University of Illinois at Urbana-Champaign (UIUC). Initial curriculum development funding for the course was provided by the Academy for Excellence in Engineering Education (AE^3), a UIUC College of Engineering organization. Autodesk Inc. also provides ongoing support for the course and the research that it fosters. In addition to gaining hands-on experience using a variety of CAD/CAE tools, the goals of this course include understanding 1) the mathematical foundations of geometric modeling, 2) the strengths and weaknesses of surface and parametric solid modeling approaches, 3) the divergent needs of design and analysis models, and how best to create design models so that they can subsequently be used for analysis, 4) the analytical skills necessary to be a successful design analyst, and 5) how best to move model information across applications.

Overview

The class meets four hours a week, with students receiving three semester credits (or 0.75 units in the case of graduate students) for their efforts. The only prerequisite is an engineering graphics course that includes parametric solid modeling, although students are also expected to be familiar with solid mechanics concepts. Class time is divided between a classroom equipped with a computer and projection system, and a computer laboratory.

In the classroom either the instructor gives lectures, or the students themselves make presentations on topics that they have previously researched. Lectures cover such subjects as transformation matrices, geometric modeling (solids, splines, and surfaces), finite element analysis, virtual engineering, rapid prototyping, CAD/CAM/CAE interoperability, collaboration tools, etc.

Housed in the same building as the classroom is an Engineering Workstation (EWS) computer lab containing thirty Dell Precision workstations supported by a Windows 2000 server. The lab includes a projection system, used for demonstration purposes, as well as printers (color and black & white) and a scanner. CAD/CAE software used in the course and delivered by the server includes Autodesk Inventor, McNeel Rhinoceros, ANSYS Workbench/Design Simulation, and MSC Dynamic Designer. Students use the lab to work on design projects and assignments, as well as to work through software tutorials. Design projects include the modeling and analysis of a backhoe linkage, surface modeling of a boat hull, and a product design/reverse engineering project.

Located on the same floor as the EWS lab, a prototyping lab houses a Stratasys Dimension 3D printer, as well as an older Genisys XS 3D printer, also from Stratasys. The Dimension has an 8" x 8" x 12" build volume, produces durable ABS plastic parts available in six different colors, is reasonably fast and accurate (to within 0.01 inches), and is not much more difficult to use that a regular printer. This room also contains two additional workstations running the same CAD/CAE course software, as well as a web server to be used to deliver materials developed in conjunction with this course (see the Research section below).

Outside the classroom and computer lab, students are expected to do reading and complete homework assignments. The textbook, references, and reserve reading list for the course is included as a bibliography at the end of the paper. Last year students took a field trip to the National Design and Engineering Show (NDES) in Chicago. This semester an on-campus field trip will be made to the Cave Automatic Virtual Environment (CAVE) facility at the National Center for Supercomputer Applications (NCSA). The course web site uses WebCT course management software.

Course Content

The original AE^3 funding proposal called for the development of a new Computer-Aided Design, Manufacturing and Engineering (CAD/CAM/CAE) course. The proposal also stated that the course would be hands-on, project-driven, and would include a product design project. Since UIUC's Department of Mechanical & Industrial Engineering already offers CAM courses, it was later decided to eliminate the CAM component of the course. This left the design (CAD) and analysis (CAE) components; prototyping was added to leverage the fact that the GE Department already had a 3D printer.

Table 1 - Course Content

Time	Lectures	Lab
Weeks 1 to 4	**Computer Graphics / Geometric Modeling** Lectures: • CAD/CAM/CAE hardware • Vectors • Graphics Libraries • Coordinate Systems • Geometric Transformations • Solid Modeling	Inventor tutorials Project work: • Backhoe modeling • Product design modeling
Weeks 5 to 8	**NURBS** Lectures: • Parametric Curves • Bezier Curves • B-Splines • NURBS • Surfaces • Hull lines plans	Rhinoceros training Project work: • Hull surface modeling • Product design modeling
Weeks 9 to 14	**Analysis** Lectures: • FEA Introduction • Finite Element Modeling • Meshing • Boundary Conditions • Convergence and Accuracy • FEA Results	Dynamic Designer training ANSYS Design Simulation training Project work: • Backhoe analysis
Weeks 15 to 16	**Miscellaneous** Student presentations: • CAD file translation • Rapid prototyping (stl files) • Group Technology • EdgeCAM software • Autodesk Streamline • Inventor welding environment • Others	Project work: • Product design modeling • Product design analysis

Table 1 shows that the course is loosely organized into four sequences. In the first segment lectures and homework assignments focus on computer graphics and geometric modeling topics. Concurrently lab time is used to model a backhoe mechanism, as well as to start the modeling of the product design/reverse engineering project.

In the lecture portion of the surface-modeling segment, the Rhinoceros software is used to illustrate such concepts as control points, order, knots, continuity, Gaussian curvature, developable surfaces, etc. After working through the Rhinoceros training materials, students then work on to the hull surface modeling project in the lab.

CAE is the focus of the second half of the semester. In the lab students first work through Dynamic Designer training materials, before moving on to ANSYS Workbench/Design Simulation[1]. This accomplished, they can now complete the second (analysis) part of the backhoe linkage project. The remainder of the lab time is spent working on the analysis portion of the product design / reverse engineering project.

The third block of lectures focus on using CAD models for finite element analysis. Design Simulation is used in conjunction with Inventor to investigate such topics as building clean geometry, mesh refinement, applying boundary conditions, conducting "what-if" studies, analyzing results, detecting and avoiding singularities, etc.

In the last lecture segment students make brief ten to fifteen minute presentations on a topic that they have previously researched. Students are provided with a list of relevant topics, from which they chose one. In reality, some of these presentations will have been made earlier in the semester than the time frame suggested in Table 1.

Course Software

An important premise of the course is that commercially available software can be used to great advantage, not only for project work, but also to illustrate core mathematical and business concepts underlying the MCAD discipline. Although turnkey CAD/CAM/CAE software solutions are available (e.g., Unigraphics, Pro/ENGINEER, Catia), the GE Department has had considerable success with Autodesk Inventor, not only in a required engineering graphics course, but also in upper level design courses.

The decision to build the course software around Autodesk Inventor naturally led to the selection of other software with close ties to Autodesk. McNeel Rhinoceros was chosen as a non-uniform rational B-spline (NURBS) surface modeler. Rhinoceros was originally developed as an AutoCAD plug-in; its command structure is consequently similar to that of AutoCAD.[2] Although relatively inexpensive, Rhinoceros has proved to be an invaluable teaching tool when called upon to help explain the mathematical complexities of NURBS. It is extremely well supported, with training sessions (free to educators) offered throughout the country on a regular basis. An educational lab license includes a vast array of training materials, including training manuals, books, and CD's. As an additional benefit, Rhinoceros is capable of both reading and writing to a great many graphics file formats, and consequently is useful for file translation purposes. Rhinoceros files saved in a neutral file format (e.g., SAT, STEP, IGES) can be imported into Autodesk Inventor (see Figure 1).

[1] ANSYS Workbench is a work platform used for developing and managing FEA simulations. Workbench currently includes three components: 1) Design Modeler, a parametric solid modeler that can be used to condition geometry for an FEA simulation, 2) Design Simulation (formerly known as DesignSpace), used to perform FEA simulations, and 3) Design Xplorer, used for design optimization. CAD geometry (e.g., Inventor files) can either be imported directly to Design Modeler or to Design Simulation.

[2] GE students use both AutoCAD and Inventor in the first year engineering graphics course.

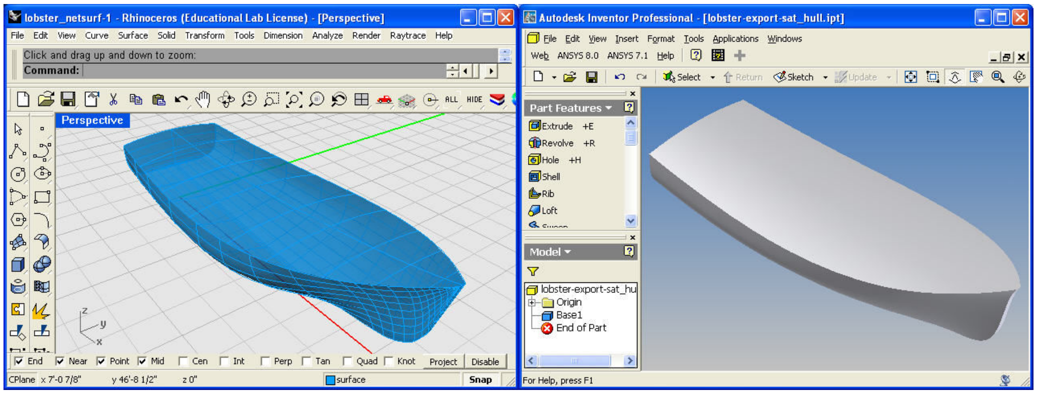

Figure 1 – Rhinoceros hull surface model on the left; on right, same file in Inventor (imported as SAT file)

The most widely used CAE software category is finite element analysis. From among Autodesk's CAE software partners, Design Simulation, a CAD-embedded finite element analysis package from ANSYS was chosen. Design Simulation offers the robustness and accuracy of the ANSYS software engine, an elegant, extremely usable GUI, and associativity with most MCAD software, including Inventor. Design Simulation can be launched from within Inventor (see Figure 2). A currently open Inventor file (part or assembly) is transferred to the Design Simulation environment, where it can be pre-processed, solved, and then post-processed. If the geometry is modified in Inventor, an update will cause these modifications to be passed along to Design Simulation. Since Design Simulation is a standalone package with its own (DSDB) file format, files can also be opened directly in Design Simulation.

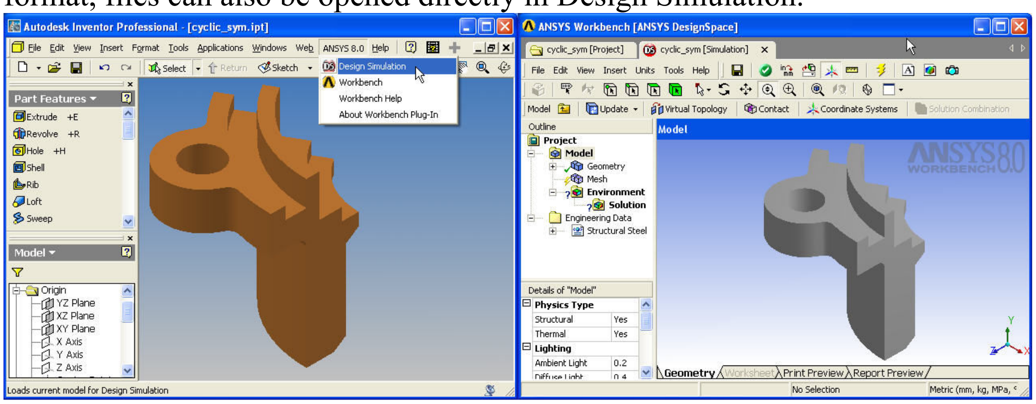

Figure 2 – On left axisymmetric part shown in Inventor; on right, same part in Design Simulation

Probably the next most commonly employed CAE software category is motion analysis. Here Dynamic Designer from Mechanical Dynamics, Inc. (MDI)[3] was selected. Dynamic Designer is a derivative of ADAMS, the market leader in the motion analysis software niche. Dynamic Designer is truly CAD-embedded; an additional (Motion) menu is appended to the CAD (in our case, Inventor) assembly interface (see Figure 3). All motion analysis work is conducted directly within the Inventor assembly environment.

[3] MSC Software has since purchased MDI.

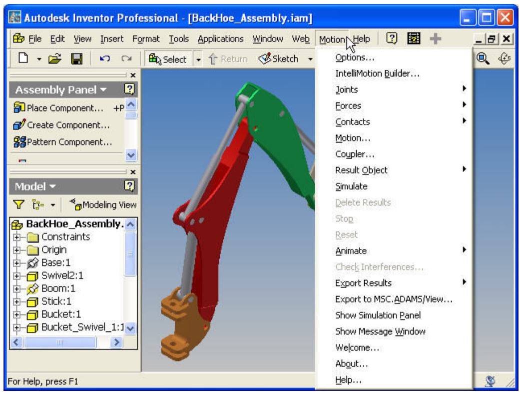

Figure 3 – Dynamic Designer motion menu, shown in Inventor

Design Projects

As was mentioned earlier, students currently work on the modeling and analysis (finite element as well as motion) of a backhoe mechanism, the surface modeling of a boat hull, and a capstone product dissection/redesign project selected by the student.

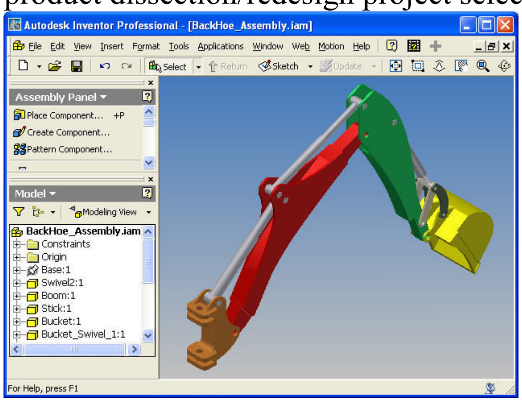

Figure 4 - Student design of backhoe linkage

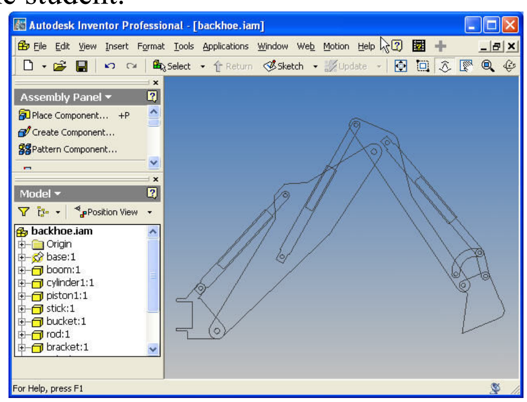

Figure 5 - 2D skeleton assembly model of backhoe

There are two parts to the backhoe linkage project, modeling and analysis. Students are first asked to model a four-degree of freedom backhoe assembly containing from 10 to 15 parts (see Figure 4). It is left to the students to select an actual backhoe upon which their model will be based. Inventor is used to create the assembly model. Students are encouraged to start the modeling process by first creating a 2D skeleton assembly model (see Figure 5), with motion simulation. As part of the project deliverables, students are required to make a 3D print of a single part (although some students have gone on to prototype the entire mechanism!).

A significant part of the analysis portion of the project is based upon the Society of Automotive Engineers (SAE) Documents (J31, J49) used for backhoe linkage design[4]. The analysis deliverables include a weight estimate, interference and collision detection, as well as structural (see Figure 6) and motion analysis (see Figure 7). Dynamic Designer is used to create an animation of a typical dig and load sequence.

[4] Thanks are owed to Caterpillar Inc., in particular Greg Metz, Jim Davis, and Jay Renfrow for their help in making the project criteria as realistic as possible.

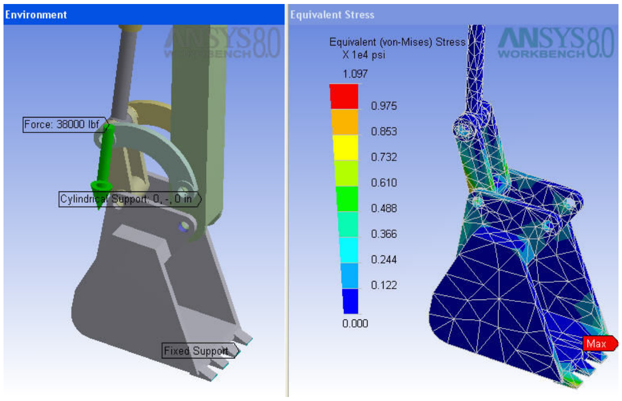

Figure 6 – Digging force analysis in Design Simulation

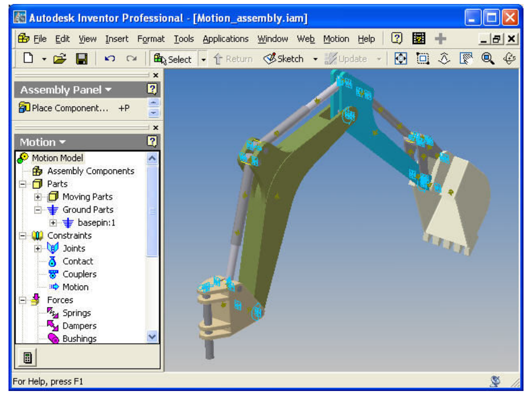

Figure 7 – Backhoe motion analysis using Dynamic Designer

The boat hull project[5] starts with the creation of a fully enclosed volume NURBS model of a hull form in Rhinoceros. In preparation, students are given a lecture on hull lines plans[6]. Lecture and training material is also provided on the use of Rhinoceros for marine design. Students are then shown a number of lines plans (see Figure 8), from which they select one. Additional features (e.g., external appendages, superstructure, internal detail) are also added to the surface model (see Figure 9). A 3D print of the surface model is required.

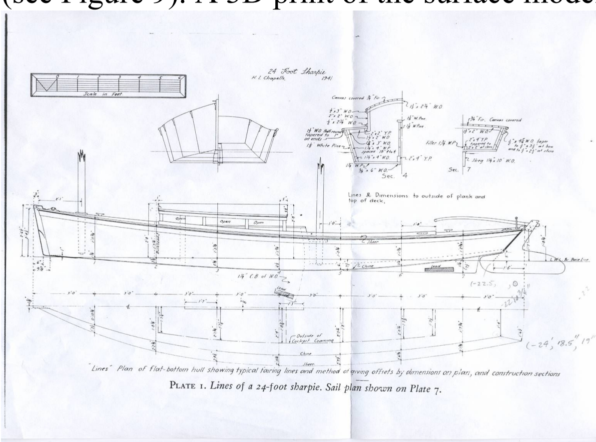

Figure 8 – Lines Plan

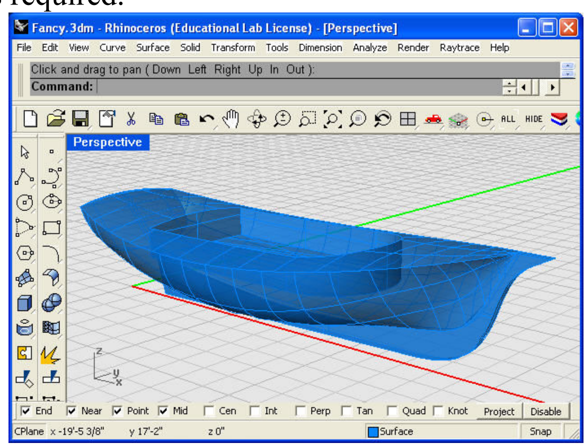

Figure 9 – Student design of boat hull

The final product design project is more open-ended than the first two. Students are asked to identify a simple product upon which the project is to be based. Examples might include vice grips, a coffee maker, a bicycle derailleur, or an adjustable desk lamp. They are also encouraged to combine this project with another course or research they are currently involved with.

The students are then expected to dissect and reverse engineer the product in order to create a virtual prototype of the design (see Figure 10). The modeling is either done in Inventor or Rhinoceros. Students are encouraged to make some improvement upon the original design. In most situations students are expected to include some form of analysis of the product, using

[5] The author is a licensed professional engineer in Naval Architecture and Marine Engineering, and spent twelve years working in the marine industry.
[6] A lines plan is a drawing that employs orthographic projection techniques to capture the 3D shape of a hull form.

Design Simulation, Dynamic Designer, or both. As with the other projects, prototyping is also a requirement (see Figure 11).

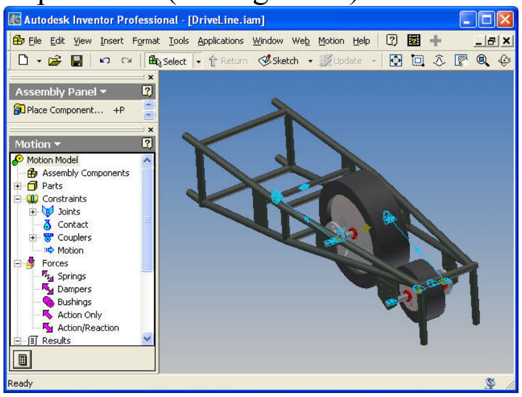

Figure 10 - Student product design project

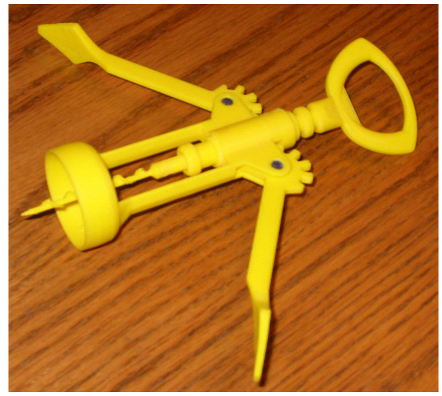

Figure 11 - 3D print of corkscrew design

Research

In 2003 the Autodesk Manufacturing Systems Division agreed to a proposal, submitted by the author, requesting funding and technical support. This support is being used to develop instructional materials demonstrating ways in which Autodesk and downstream partner software can be employed to integrate a modern engineering mechanics curriculum. As part of this agreement, any materials developed in the course of this research for use in the GE curriculum will also be made available to other educational institutions via the Internet.

As a start, a GE master's thesis candidate is currently working to create an instructional software package to assist in the development of competent design analysts. Using Design Simulation in combination with Autodesk Inventor, best practices, guidelines, and rules of thumb relevant to the use of CAD-embedded FEA have been identified. Virtual models and simulations are currently being developed to illustrate these guidelines, as well as for software training purposes. The completed interactive multimedia package is being developed using Macromedia's Authorware, and includes structured learning objectives, hypertext links, and video tutorials.

This work is motivated by the fact that software like Design Simulation allows a company engaged in product design and development to perform engineering analysis early in the design process. While design engineers, with their familiarity with CAD, are probably best suited to conduct this upfront analysis work, they are not analysis experts. Working under the supervision of an analyst specialist, however, and coupled with the help of instructional software that attempts to capture a portion of the expertise of an experienced analyst, design engineers are certainly capable of taking on this innovative new role.

Other potential research topics include the following:

- Develop a library of virtual mechanisms, as well as physical prototypes, for use in an engineering mechanics curriculum.
- Develop instructional materials that capture manufacturing know-how (e.g., guidelines, best practices, rules of thumb) relevant to product design.

- Develop instructional materials that focus on the employment of hybrid (i.e., combination of parametric solids with surfaces) modeling techniques.
- Investigate the use of Autodesk's Streamline and Vault workgroup data management technology together with Inventor to work collaboratively on a design project, conceivably with other academic units.
- Expand upon the FEA Design Simulation instructional materials project described above. This expanded project might include such topics as thermal, modal, buckling, and fatigue analysis, as well as scenarios where it is necessary to employ traditional ANSYS, rather than Design Simulation.

Conclusion

This paper describes a new course offered by the Department of General Engineering at the University of Illinois at Urbana-Champaign. Some of the course goals include understanding the mathematical underpinnings of computer graphics and geometric modeling, exposure to both parametric solid assembly and NURBS surface modeling, experience with CAD-embedded finite element and motion analysis software, appreciation for the analytical skills needed to be a successful design analyst, CAD/CAE interoperability issues, experience with 3D printers, etc.

Given the increasing power and interconnectedness of CAD and CAE software, this project-driven course also aims to build bridges between the design and analysis courses common to a structural mechanics curriculum. This is accomplished in part by using the course as a platform for developing instructional materials that can be used throughout the curriculum.

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