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Team-Based Design-and-Build Projects in a Large Freshman Mechanical Engineering Class

Dr. Mario W. Gomes, Rochester Institute of Technology (COE)
Dr. Elizabeth A. DeBartolo, Rochester Institute of Technology (COE)

Dr. Elizabeth A. DeBartolo is an associate professor in the Mechanical Engineering Department at the Rochester Institute of Technology. She works with students on the design of assistive devices and rehabilitation aids, and characterizing the mechanical behavior of materials. Dr. DeBartolo serves on her college's leadership teams for both multi-disciplinary capstone design and outreach program development.

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Abstract

In 2013-14, RIT will be undergoing a significant curriculum change. As part of this change, the freshman Mechanical Engineering experience is being redesigned to incorporate a comprehensive freshman design experience. This paper describes the development of a design and build project that is being piloted during 2012-13, to be launched full-scale during 2013-14.

The project for this course must satisfy a number of constraints:
- Accommodate large class sizes: plan for nearly 300 students per year
- Limited financial and personnel resources: $10/student and existing machine shop staff
- Respect for departmental history: freshmen must still make the traditional machinist's hammer that has been part of our curriculum for decades
- Allow students to be creative in a meaningful way
- Pose the problem in such a way that there is not one obvious solution
- Require collaborative effort within teams (and between teams, if possible)
- Require analysis appropriate for students who have completed high school physics and pre-calculus

The project identified for this course is to charge students with designing a mechanical musical instrument that will play a song on metallic chimes. This project satisfies all the required constraints, and even allows students to incorporate the historical freshman hammer into their apparatus to strike the chimes. This paper will discuss how the constraints have been addressed in the design of the project, and how the project will be integrated into a course that will cover design process, in addition to basic skills in CAD, machine shop operations, and teamwork.

Introduction

At RIT, students in the Mechanical Engineering program have their first significant design and build experience in their capstone engineering design course. Several earlier courses in the curriculum include elements of design and manufacturing, but never tied together in a single experience where the students are charged with developing a design on paper, building a prototype to their own specifications, and testing the prototype performance. Once students reach the capstone design course, they are frequently unprepared to apply the design process to an open-ended problem and carry the solution through to building and testing. The design experiences leading up to the capstone course currently include:

<u>Manufacturing a machinist's hammer in a first-year lab</u>. While this gives students valuable hands-on time in the machine shop, they do none of the design work and, due to time and personnel constraints, very little of the machine setup.

<u>Open ended design project in a CAD course</u>. This project is open-ended, and creativity is encouraged, but this is a design on paper only, and no analysis is required; it is strictly a demonstration that they can create a 3-D solid model using a prescribed set of CAD operations.

Paper design in a Design of Machine Elements course. Although this project has a heavy emphasis on analysis, it is also a design on paper only.

Laboratory validation of analytical model. In a lab course focused on Thermo/Fluids, students build their own simple test rig and compare experimental results to an analytical model related to their choice of topics within Thermodynamics and Fluid Mechanics. However, this is only a one-credit lab, and the topics are limited.

Open-ended design and analysis project. In a third-year course, students learn the design process and apply it to a design problem that is carefully chosen to require the application of all core engineering science courses required for graduation. This course was recently removed as a requirement from the undergraduate curriculum. This was a design on paper only.

As part of a major curriculum revision, RIT has developed a freshman course that exposes students to the full design cycle, from problem definition through to prototype testing. The course integrates topics from the introductory courses in CAD, machine shop lab, and design process, using a hands-on, open-ended design project as the context for the material covered in the class. The project will be team-based, in order to give students experience with team dynamics, professional team behavior, and peer evaluation. The design project is the focus of this paper. While the concepts of creating integrative first year engineering courses [1-2] and first-year design-and-build projects [3-7] are not new, the constraints placed on the design project posed an interesting challenge.

Design Project Description

After brainstorming a number of solutions, the chosen project was to have students build "Robochime", or an automated system that plays a song on a set of chimes. Each student on a team is responsible for a mechanism to strike at least a single chime, and the team is responsible for combining the individual notes to play a song of their choosing. This project is scalable, and requires teamwork. The chime strikers are actuated with a series of spring-return solenoids controlled by an Arduino microcontroller. The program is written in C and, at a minimum, only requires students to customize the order in which the solenoids move and the delay between successive strikes. Each team receives a kit of supplies (Table 1) that contains both the materials necessary to minimally satisfy the project requirement, and additional materials that can be used to go beyond the basic requirements. Additionally, students are able to use all or part of the machinist's hammer, which they make in the Machine Shop during the first part of the quarter, in their mechanisms. In order to entice students to do more than the minimum, a series of challenges are issued to build the mechanism (1) with the smallest footprint, (2) that plays the most notes, (3) that moves the most mass on a striker, and (4) that has the largest total mass of chimes. Figure 1 depicts the

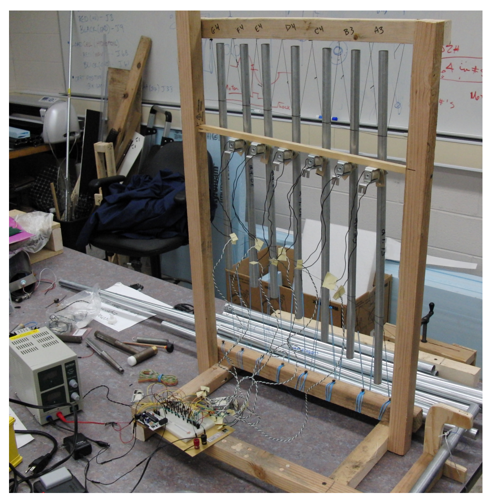
Figure 1. "Robochime" prototype.

instructor's mock-up of the project (not shared with the students ahead of time) and Table 2 shows the ways in which the project constraints were met.

Table 1. Project kit contents (* item that must be returned, fully functional, at the end of the term.)

*5 spring-return 12 VDC solenoids	50 g oil-based clay	25 2-1/2" drywall screws	1'x1' pegboard
*1 double adjustable gearbox motor (Tamiya)	8' 2x4 lumber (ripped lengthwise)	26 1" drywall screws	3' 8 conductor 24AWG ethernet cable
*4-speed crank angle gearbox motor (Tamiya)	20' of galvanized steel conduit	3 12D common nails	5' 20 conductor 28AWG ribbon cable with 20-pin header
*100 g Shapelock™	3 long balloons	35 3D finishing nails	1 flexible pull cable with housing
*25 small wire nuts	15 jumbo popsicle sticks	2 small and 1 big balloon	30' high-strength polyester thread
9 permanent adhesive mounting tabs	5 butterfly and 10 jumbo paperclips	3 medium and 3 large zip ties	30 small and 10 large rubber bands

Table 2. Means of addressing project constraints.

Constraint	**Solution**
Accommodate large class sizes: plan for nearly 300 students per year, and approximately 70 in 2012-13 pilot offering.	Team-based project, all students given the same design challenge with measurable outcomes.
Limited financial and personnel resources: $10/student and existing machine shop staff	Kit of materials with a combination of consumable and reusable parts.
Allow students to be creative in a meaningful way	Students can select their own song based on a set of engineering constraints (material length available, # chimes they can strike) as well as design their own chime and striker supports.
Respect for departmental history: freshmen must still make the traditional machinist's hammer that has been part of our curriculum for decades	Students must use some part of the hammer in the striker.
Pose the problem in such a way that there is not one obvious solution	Offer prizes for winning various challenges
Require collaborative effort within teams (and between teams, if possible)	Chimes must be in tune with one another, and strikes must be timed appropriately.
Require analysis appropriate for students who have completed high school physics and pre-calculus	Calculating chime length, constrained by the song choice and material availability, can be simplified from differential equations to basic algebra.

Course Description

The course learning outcomes related to this course are:

1. Implement a structured design process to solve an engineering problem, from identification of customer needs through prototype testing.
2. Use an industry standard CAD package to create a complete parametric 3-D solid model.
3. Demonstrate professional and ethical behavior as an individual and a team member.
4. Read a part drawing, in order to fabricate and inspect that part to specification.

5. Communicate design information using written, graphical, and verbal means.

These are all addressed and measured in the context of the design project and associated assignments.

The format of the design portion of the course during the 2012-13 academic year is a single 2-hour workshop format meeting period that includes time for instruction and hands-on work. All students taking this course are co-registered for the department's introductory CAD course; in the long term, the CAD content will become part of the single comprehensive design-build-test design project deliverables course. The outline for the design portion of the course and the project deliverables are summarized in Table 3, along with the parallel CAD components.

Table 3. Course outline: Design content + Project, with CAD content provided for context.

Week	Design Components	Design Project/HW Assignment	CAD Components
1	Design process, needs assessment	List of potential songs, selection criteria, teambuilding activity plan	Sketching
2	Functions & constraints, teamwork & conflict resolution	Functional decomposition, constraints, team norms, teambuilding activity debrief	Dimensioning, extrudes
3	Concept selection, brainstorming	Brainstorming ideas (chime structure), Pugh analysis (song choice)	Tolerances, revolves, datums, holes
4	Moments of inertia, free vibration models	Concept selection (chime structure), analysis of chime lengths, hand sketch of final design concept	Patterns, shells, family tables
5	Tolerance and error propagation, cut chimes, program microcontroller	Tolerance for chime length/pitches, song program	Sweeps, blends, material properties
6	Pitch testing	Pitch test results/plan for changes, initial CAD assembly	Patterns, advanced holes and threads, copy/mirror
7	Project build time	Final CAD assembly, table of parts for chime lengths	Assembly with constraints
8	Ethics, subcomponent testing	1-week team plan	Starting a drawing, assembly drawings
9	Subcomponent testing, project build time	1-week team plan	Drawings, CAD libraries
10	Subcomponent integration testing, work time	1-week team plan	Drawing comments
Finals	Final presentations, check-in project materials	Final video of device playing your song + 2 minute discussion of your design	Hammer drawing package due

The instruction is delivered just-in-time, with project deliverables due immediately after covering the relevant content in class. The course follows the design process, with project-specific instruction given as-needed during the quarter. The process the students follow is:

Problem Definition➔Brainstorming➔Pareto voting➔Selection criteria creation➔...
…Pugh concept selection [8]➔Detailed design➔Construction➔Testing➔Redesign

This process is implemented twice: once for the selection of the song the team chooses to play and once for the design of the actual chime structure. This approach gives the students a chance to practice a few steps of the sequence twice within one class term.

It is important to note that, once the final designs have been submitted, the class shifts to in-class work time for the project build, and for subcomponent testing, which keeps the class project-focused. Teams also shift at this point from submitting project-related homework, which is instructor-driven, to submitting their team's plan of work for the coming week. This begins to shift the burden of assigning work to the team members themselves.

The engineering model and analysis central to this project are the concepts of free vibration and frequency analysis. Even though the class is intended for incoming freshmen with only high school physics and pre-calculus required, the differential equation analysis required can be simplified to a simple algebraic expression that any incoming engineering student should be able to manipulate. A mathematical model of an elastic vibrating beam with free-free end conditions is presented to the class after they have chosen the song they want to play, but before they finalize their chime design. The frequency of the fundamental mode of vibration for a free-free beam is described by [9]:

$$f_1 \approx \frac{22.373}{2\pi}\sqrt{\frac{EI}{\rho A l^4}}$$

where f_1 is the desired fundamental frequency in Hz, E is the Young's modulus of the beam material, I is the second moment of area (or area moment of inertia) of the cross-section of the beam about its neutral axis, ρ is the density of the beam material, A is the cross-sectional area of the beam, and l is the length of the beam. This model allowed the students to make predictions for the chime length that corresponds to each note (frequency) in their song. Given the 20 ft. of total metal conduit length, the model allows them to determine if the desired number of notes can be built from the given conduit.

Once each team has cut their chimes, the chimes are tested for pitch. Based on their analysis, students know what frequency they are expecting. Because of measurement errors, material variability, and manufacturing tolerances, the actual measured frequency may vary slightly from the design frequency. Students use a microphone, a computer, and the open-source Audacity software to measure the frequency spectrum of the impulse response of their chimes and record the location of the peak near the desired fundamental frequency. The relative error in frequency is then calculated and possible reasons are given along with estimates of the magnitudes of those errors and the effect they would have on the predicted frequencies.

Samples of Student Work:

Since this pilot project is currently in processes, we have only the initial samples of student work. To date, we have examples of student work covering brainstorming, identification of selection criteria, and Pugh concept selection [8] of the song for their chimes to play; and functional decomposition and brainstorming for their Robochime system.

Sample Song Brainstorming:
Students are graded on their brainstorming list (quantity of ideas) and quality of their selection criteria (well thought out, described so that they are understandable).

- Mary Had a Little Lamb - Lowell Mason
- Frère Jacques – ??
- Twinkle Twinkle Little Star - Ann & Jane Taylor
- The Old Grey Goose is Dead - David Allan Coe
- The Addams Family Theme - Vic Mizzy
- Ring of Fire - Johnny Cash
- Knockin' on Heaven's Door - Bob Dylan
- Good Morning to You - Patty Hill
- Eleanor Rigby - The Beatles
- Sweet Home Alabama - Lynyrd Skynard
- Smoke On the Water by Deep Purple
- Beethoven's 9th by Beethoven
- Lack of Communication by Ratt
- Back In Black by AC/DC
- Sweet Child of Mine (~ 1 min intro only) by Guns n Roses
- Slow Ride by Foghat
- Here Comes the Sun by The Beatles
- Dream On by Aerosmith
- Children of the Grave by Black Sabbath
- Holiday by Green Day

Possible criteria for song selection:
- Playable on chimes
- Notes are separate or simple chords
- Max of 10-15 different notes
- Repetition would make it easier
- Appropriate lyrics
- Simple melody
- Consists of only a few notes and have a slow tempo
- Be recognizable otherwise no one will know what we are playing
- Should only consist of a few instruments to allow all aspects of the song to be illustrated by the chimes

Sample Pugh Chart for song selection:
In order for a reasonable number of songs to be examined in more detail, standard Pareto voting was used to focus the teams number of songs from 40 to around 8-10 songs. Students were then required to read Stuart Pugh's original article on concept selection techniques [8], and implement those techniques. The example illustrated here (Figures 3 and 4) shows how a team used the Pugh selection process once, to identify some key frontrunners in their list of concepts, then repeated the process with one of those frontrunners chosen as a datum, in order to force further distinction between the two.

12/15/12 5:25PM	GROUP 3 PUGH CHART							
SONGS/CRITERIA	1	2	3	4	5	6	7	8
A	+	-	S	+	+	-	S	D
B	-	+	+	S	-	-	+	
C	-	+	+	+	-	-	-	A
D	S	S	S	S	S	S	S	
E	+	S	+	+	+	+	-	T
F	S	-	S	S	S	-	-	
∑+	2	2	3	3	2	1	1	U
∑-	2	2	0	0	2	4	3	
∑S	2	2	3	3	2	1	2	M

Song Representations:	
1	Zelda's Lullaby
2	Fireflies
3	You and Me
4	Sweet Child O' Mine
5	Smoke on the Water
6	Star Trek Theme Song
7	RIT Alma Mater
8	Jingle Bells
Criteria:	
A	Relative Complexity
B	Close to 1 octave
C	Bewteen 5 and 8 notes
D	Does it have sheet music?
E	Is the song likeable?
F	Easy to identify

Figure 3: First iteration of Pugh selection for song.

12/15/12 5:25PM	GROUP 3 PUGH CHART							
SONGS/CRITERIA	1	2	3	4	5	6	7	8
A	+	-	D	+	+	-	S	S
B	-	+		-	-	-	-	-
C	-	S	A	S	-	-	-	+
D	S	S		S	S	S	S	S
E	S	-	T	+	-	-	-	-
F	S	-		+	+	-	-	S
∑+	1	1	U	3	2	0	0	1
∑-	2	3		1	3	5	4	2
∑S	3	2	M	2	1	1	2	3

Song Representations:	
1	Zelda's Lullaby
2	Fireflies
3	You and Me
4	Sweet Child O' Mine
5	Smoke on the Water
6	Star Trek Theme Song
7	RIT Alma Mater
8	Jingle Bells
Criteria:	
A	Relative Complexity
B	Close to 1 octave
C	Bewteen 5 and 8 notes
D	Does it have sheet music?
E	Is the song likeable?
F	Easy to identify

Figure 4: Second iteration of Pugh selection for song.

Functional Decomposition for Robochime:

As part of the Problem Definition phase, students are introduced to the concept of functional decomposition, as described by Ulrich and Eppinger in [10]. Students perform a functional decomposition of their Robochime design, in order to facilitate brainstorming (i.e., brainstorming around functions, rather than brainstorming complete system concepts). A sample functional decomposition from a student team is shown in Figure 5. This allowed the team to focus their brainstorming on the core functions which were most fruitful for brainstorming (Figure 6).

The next stages for the students to complete are a Pugh chart analysis for their device design, using the same process they applied to select a song, create sketches and CAD drawings of their device (for center of mass calculations and for sample 3D online 3D printing quote), construction, testing, and redesign.

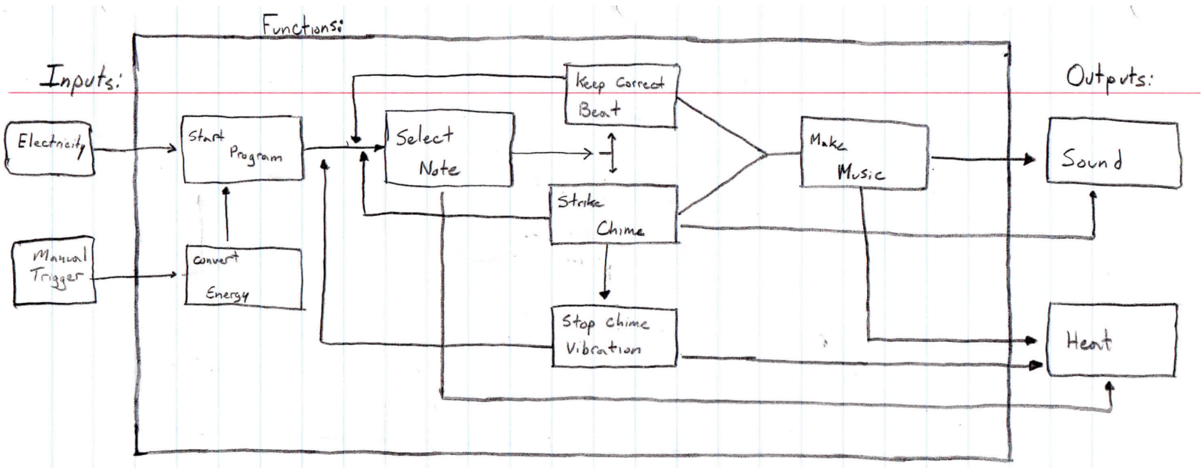

Figure 5: A student team's functional decomposition

Future Assessment:

The ultimate test of the success of this course will not ultimately be seen until the students enter their final year and participate in Multidisciplinary Senior Design (MSD). Some of the long-term questions that will be asked once these students reach senior design (2016) are:
-Q1: Does the introduction of this course improve students' final year MSD experiences?
-Q2: Does the integration of Design/CAD/Machine shop improve retention of those skills?

In the short term, we will provide answers to the following more immediate questions with the initial implementations of the course:
-Q1: Does this course successfully integrate CAD and design topics?
-Q2: Does this course successfully integrate Design and Machine Shop topics?
-Q3: Does this course successfully integrate Machine shop and CAD topics?

Data collection is the first step in trying to answer these questions, and a survey will be given to the students participating in the pilot course.

Summary:

The introduction of this integrated freshman design/build/test course has started and the initial results are promising. We were able to design the project to meet the budget, time, and resource goals. Qualitatively, the students are excited about the design project and are using the analysis for chime frequency to help them make high-level design decisions for their device. There is still a significant portion of the project yet to be completed by the students and we hope our future assessment plans can improve the project for the next iteration.

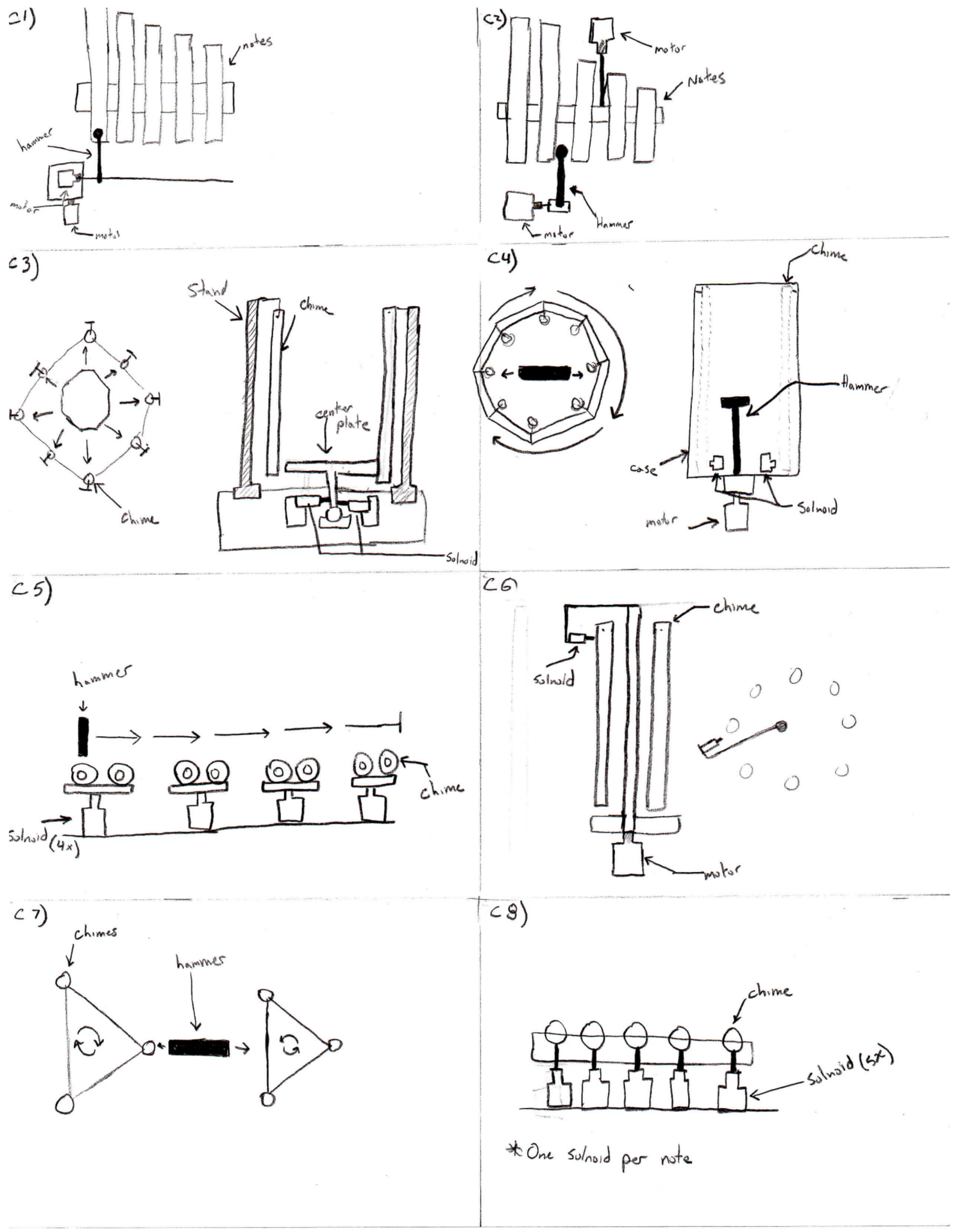

Figure 6: Half of the brainstorming results for the function of "selecting a note" from Figure 5.

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