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BYOE: Engineering Mechanics with a Twist: Design and Implementation of a Custom Torsion-Testing Apparatus

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Abstract

The primary value of laboratory courses is that they enable students to experience lessons in a hands-on way. This hands-on approach enables students to see, understand, and believe the results of an experiment much more deeply than simply hearing about the results of others. One of the main challenges, however, is finding the resources (time, space, and money) needed to prepare and carry out experiments. In this paper, we present a novel torsional-testing device that was developed to explore the concept of torsion loads, shear stress, and the shear modulus (or modulus of rigidity G). This device has been successfully used by students to determine the modulus of rigidity for three different (re-usable) material samples in an undergraduate mechanics laboratory course. This paper presents information regarding the design and application of this device in the classroom. This torsional-testing device contributes to the field in several ways. First, it is low in cost (total materials cost is less than $500 USD). Second, the testing system is compact. It can easily be carried by one person and is small enough to fit on a desktop. Third, testing can be performed quickly and easily with no tools required. The development of the device is complete, saving instructors the cost and effort required to either develop their own solution, or to purchase (or adapt) another (likely costly) testing option to meet their needs. The torsion-testing experiment is used to teach students how to write the "Method" section of their lab reports, and represents one out of a series of twelve to fourteen experiments (depending on the semester). Compared to previous semesters, in which a much more complicated custom torsion-testing device was used, we found this device to be much faster and easier to operate, and student descriptions of the experimental setup were also more comprehensible, perhaps due to the simplifications afforded by this system.

1 Background

Experimentation is at the core of the scientific method. As we train students to become scientists and engineers, it is important to also provide training in the scientific method, and a recognition that a reliance on empirically demonstrable, replicable results is essential to what we do. This is essential for individuals responsible for designing the cars, airplanes, cellular devices, and energy systems of the future, because these devices must function properly in the physical world. A full history of the scientific method, and its role in the natural sciences is provided in [1]. Other support for using experimentation as a tool for building student knowledge stems from John Dewey [2], as well as the constructivist teaching philosophy, which traces its roots back to Jean Piaget [3], Lev Vygotsky [4], Jerome Bruner [5, 6], and David Ausubel [7, 8]. Dewey's educational philosophy focused on learning by doing, and emphasized that learning is most effective when it is active and experiential. Jean Piaget characterized learning and development through different cognitive stages, and conceptualized the learning process as an acquisition and modification of knowledge structures he called schemas through the processes of assimilation and accommodation [3]. Vygotsky is known in education for his development of the concept of the zone of proximal development, which is a way of describing the gap between what a student may learn on their own versus with the appropriate support [4]. This concept is important in education as the presence of a larger amount of learning with support validates the work that teachers do to design learning experiences and social interaction for students. Bruner's contributions in educational psychology focused on the concept that student learning should be spurred by interest and an understanding of the interrelation of ideas and concepts rather than facts alone [5, 6]. David Ausubel also followed the ideas of Piaget, in the sense that he supported the ideas put forth for cognitive development and the importance of understanding concepts and their interrelations, but criticized the idea of discovery-based approaches to learning that suggested that students independently identify topics and direct learning rather than benefiting from more structured and carefully designed learning experiences. He also researched the use of advance organizers in teaching and was a strong component of carefully structured learning [7, 8].

The use of experimentation to teach, and also the design of a laboratory with hands-on experiences that relate to the corresponding class is related to these ideas in several ways. First, in-class experiences can be considered as a type of advance organizer for the concepts taught in lab. Second, the hands-on lab experiences helps students tie the concepts to concrete physical phenomena rather than mere abstractions. Finally, the reinforcement of an empirical approach to scientific knowledge underscores the importance of relying on real-world behavior to guide understanding and engineering design.

One of the guiding principles for the design of lab activities for this project was that lab activities are most effective if they align closely with concepts and principles taught in class. In addition, lab activities should allow students to visualize, experience, and clarify confusing concepts. To this end, equipment should be as simple as possible so that students don't get lost in aspects of the experiment that are not at the core of the phenomena studied. Unnecessary programs, gadgets, tools, or assembly should be avoided when possible. Further, sufficient equipment needs to be provided so that students can all conduct experiments first-hand, rather than simply watching others perform experiments. Thus, it is better to have multiple sets of simple-to-use equipment, as opposed to one or two pieces of complicated equipment, even if more complicated equipment is more capable. Finally, equipment should be as low in cost as possible.

Understanding the structure of the lecture course this lab accompanies is critical to understanding the corresponding lab structure, and the part the equipment developed aids in teaching course content. For the mechanics of materials class which this lab accompanies, the course content can be divided into four main sections: axial loading, torsional loading, transverse loading, and other topics. Axial loading includes tensile testing, compression testing, and column buckling. It covers concepts of normal stress, normal strain, and tensile parameters (e.g., yield strength, ultimate strength, elastic modulus, failure strain). This is a natural place to start since it only involves loading along one axis, and the stress distributions are uniform in this direction. Torsional loading has only one dimension of loading, also along the long axis of the structure, but this is a moment along that axis, so the shear stress distribution is slightly more complicated, and this works well as the second major section of course content. Transverse loading is more complex not only because a single force in the transverse direction can cause both normal and shear stress, but also because these stress distributions are non-uniform. This works well as a third section of course content. The final section brings concepts not covered previously such as pressure vessels, stress concentrations, stress transformations, Mohr's circle, and failure theories.

For the first and third main sections of course content, a custom universal testing machine used. The design of the universal tensile testing machine used has been presented previously [citation withheld in draft to maintain author anonymity]. Several weeks of labs walk students through the process of conducting tensile tests, determining material properties, and even column buckling. The third section covers transverse loading, and the universal testing machine is again used to conduct a three-point bending experiment. The fourth section of the course uses a variety of other equipment and will not be covered in detail here.

The universal testing machine cannot easily be used for the second section of the course, which covers the topic of torsional loading. In an effort to devise a contraption to address the need to teach about torsion, previous faculty developed a torsion testing device, pictured in Figure 1. This device was designed to allow testing of a round section in torsion, and consisted of a two ends: a fixed-end support, and a rotating-end support. The fixed-end support consisted of a large section of milled aluminum with a round hole to accept collet chuck with a flat spot machined on one side of the inserted shaft. The rotating-end support consisted of a Jacobs chuck mounted in a pillow-block bearing. A large wheel was mounted to the rotating-end support onto which a cable was wound. Weights with a slot machined into them were hung from the cable on the rotating wheel.

2 Existing System

Although it was cumbersome and difficult to use, this system allowed students to experimentally determine the modulus of rigidity of a test sample. To do this, the Allen key holding the fixed support collet chuck had to be loosened so that the chuck could slide laterally to allow for insertion of the test sample rod. After inserting the test sample into the device, the collet chuck was slid back and again secured by tightening the Allen screw. This allowed the test sample to rest inside the chucks at both ends. Next, the spanner wrench had to be tightened to hold the fixed end of the sample firmly in place. The test sample had flat spots machined so that it was able to be held firmly and did not twist within the grip. After tightening the spanner wrench to secure the sample on the fixed end, the Jacobs chuck was tightened to secure the rotating end to the sample. This was done with a Jacobs key. For one of the two models, angle indicator needles could be secured to the sample by separating the aluminum holders into two parts that were joined with a dovetail joint. After sliding the two parts together, a small Allen key was used to secure the angle indicator needle to the sample. In the second (earlier) model, the angle indicator needles could not be separated and had to be placed on the test sample before it was inserted in the ends. After securing the angle indicator needles, and ensuring they were both at the same angle, a load was placed on the cable by sliding it through the slot and resting it on the milled aluminum end support. An angle of twist was then determined by examining the difference in angle between the needles. The torsional load was calculated by multiplying the weight by the radius of the wheel. Using the equation for angular deflection of a torsionally-loaded rod

$$\phi = \frac{TL}{JG},$$

Figure 1: Previous Torsion-Testing Machine

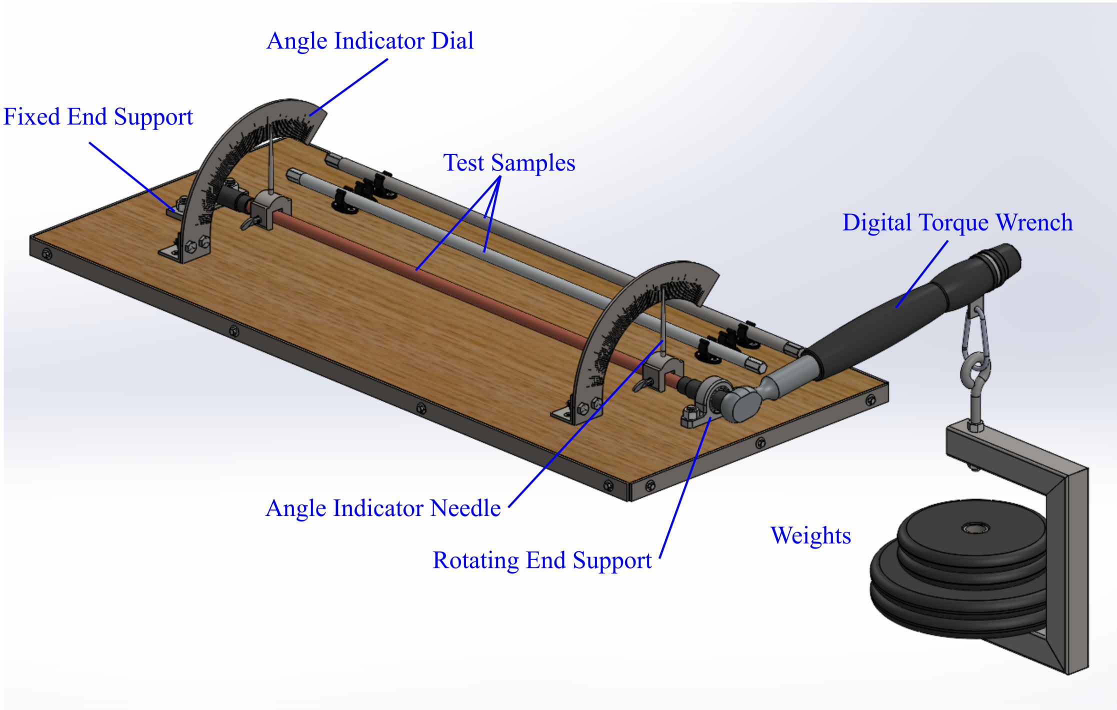

Figure 2: Improved Custom Torsion-Testing Machine

and re-arranging to solve for modulus of rigidity gives

$$G = \frac{TL}{J\phi}.$$

Substituting the appropriate polar moment of inertia $\left(J = \frac{\pi d^4}{32}\right)$ gives

$$G = \frac{32TL}{\pi d^4 \phi}.$$

There were two main problems with this system. First, it was difficult to use. Second, we only had two of these custom-made torsion-testing machines available. One option was to build more following the existing model. The second was to re-design this system to make it easier to use and easier to manufacture, then to make more. As engineers, we naturally gravitated to the second option.

3 New System

As mentioned previously, the main problems to be solved were ones of usability and manufacturability. The actual design process was an iterative process of experimentation and testing, but here we present the final product and how it addresses the main problems with the previous system. The new system design is shown in Figure 2. First, there are no legs. The system was mounted to a 14 by 33.5 in plywood board so that it would be smaller and more compact to store.

Second, this model uses test samples with the same geometry as the original. The reason for this is that the test samples worked well with the reasonable load used (approximately 20 lb), and the results were within 10% of published values, so this seemed close enough to be useful for this educational setting. These samples are 1/2 in diameter solid rods which measure 27.75 in long, with a 7/16 in hex machined into the last 3/4 in of each end of the sample. Each test machine uses steel, copper, and aluminum samples. Next, the fixed-end support was made by welding a 7/16 deep socket to a steel support, which was then bolted to the plywood base. Securing the fixed end was now as simple as sliding the hex end into the socket. For the rotating end, a teflon-coated journal bearing was used, which was also mounted to the base with 3/8 in plow bolts. Because the wheel on the end was very bulky, we decided to apply the load using a digital torque wrench. This would allow the load to be applied easily, and provided a digital readout. The new design for the load application system uses a welded steel frame with a circular peg to hold standard plate weights with a 1.0 in hole. This avoids the need to machine a slot into the plate weights as the previous design required. It also avoids the need to precisely measure the mass of the weights beforehand as the digital torque wrench gives the applied torque directly. The assembly is attached to the torque wrench using hook, which attaches to a pear ring attached to a rubber hose bracket, which is secured to the torque wrench handle. For the angle indicator dials, the previous models were quite nice, with numbers milled out of aluminum plate. A similar design was adopted, but with an angle bracket used to secure the angle indicator dial to the machine platform. For the angle indicator needles, the main goal was to have a system that was easy to use, and did not require tools. This was one of the most novel items of the whole system and required several prototypes to get right. In the end, the angle indicator needle holder is machined from aluminum, and uses a thumb screw on the side to secure it to the test sample. Finally, a 3/4 in wide steel band was screwed to the edge of the plywood to give a finished look, and locking clamps are used to secure the apparatus to the table. A picture of the finished system secured to a table is shown in Figure 3, and an image showing 12 new torsion testing systems in the open storage cabinet is shown in Figure 4. Overall, the 12 torsion-testing systems provide the ability for many more students to conduct the experiment, and take up less floor space than the previous side-by-side testing system with its stand.

Construction process After design and prototyping was completed, materials were ordered at the end of the school year, and a student was hired to help with the build and assembly work. With some guidance, the student worker cut and stained the build platforms, assembled parts, and fabricated the brackets to hold parts to the system platform. The initial angle indicator needle brackets were made with a 3D printer, and the angle indicator dials were made from foam board and a printed paper glued to it. Machining was needed for the work on the ends of the test samples, milling and finishing the aluminum angle indicator needle brackets, and making the angle indicator dials. All machine work was completed by students in one of the CAM courses in the engineering technology program, under the supervision of that course instructor. Although this project may not seem that significant, because work was mostly done by students, and assembly was done between breaks, the project took approximately two years from initial project conception to completion.

Figure 3: As-Built Custom Torsion-Testing Machine

Figure 4: Cabinet with 12 custom torsion-testing machines

4 Materials and Cost

A list of materials and the approximate cost of materials at the time of submission is provided in Table 1. The single most costly material was the digital torque wrench, which represents approximately half the cost of the overall system. Because machining work was done by students, this is not included in the cost, but the cost to prepare the tooling and perform that machining work would also likely represent a significant portion of the overall budget. Another factor to consider is that, sourcing metals from a local rather than online supplier can result in a lower cost. Local suppliers were used where possible, but online sources are used for the table provided in order to be more transparent, but still provide an approximate cost. Larger quantities may need to be ordered, but cost was scaled so the price listed reflects the price for only the items needed to build a

Table 1: Materials Breakdown for Custom Torsion-Testing Machine

Description	Vendor	Part no.	Price (USD)
Pear Link	mcmaster.com	3712T22	5.68
Dry-Running Mounted Sleeve Bearing	mcmaster.com	2820T8	28.30
Holder for 1/2 to 9/16 in Item Diameter	mcmaster.com	1171A69	25.50
Steel Spade-Head Thumb Screws	mcmaster.com	90181A542	1.08
Torx Flat Head Wood Screws	mcmaster.com	3597N15	0.42
Mounting Plate for U-Bolt	mcmaster.com	2936T112	0.29
Routing Eyebolt with Nut (3/8-16)	mcmaster.com	9489T715	1.02
Hex Head Screw (1/4-20), 3/4” Long	mcmaster.com	92865A540	0.12
Plow Bolt (3/8-16), 1.5 in Long	mcmaster.com	90911A816	0.48
Steel SAE Flat Washer (3/8)	mcmaster.com	90126A031	0.28
Hex Nut (3/8-16)	mcmaster.com	95462A031	0.64
Hex Head Wood Screws	mcmaster.com	98392A480	1.98
Angle Indicator Needle	grainger.com	45T230	2.72
Cast Iron Weight Plate w/1-in Hole (10 lb)	amazon.com	B00IHM82US	14.99
Cast Iron Weight Plate w/1-in Hole (5 lb)	amazon.com	B00IHM834I	12.11
3/8 Drive 7/16-Inch Deep Impact Socket	amazon.com	B000GTJEF2	22.06
Locking Clamp	amazon.com	B075GZJ37N	27.98
Stainless Steel Cable Clamp	amazon.com	B01MRI0ITJ	1.09
Torque Wrench, 3/8” Drive	amazon.com	B01AY0JF42	161.61
Plywood Base (23/32 in)	homedepot.com	439614	4.89
Steel Sample (1/2 in), 27.75 in long	onlinemetals.com	4793	8.99
Copper Sample (1/2 in), 27.75 in long	onlinemetals.com	15269	71.54
Aluminum Sample (1/2 in) , 27.75 in long	onlinemetals.com	18113	11.13
Aluminum Plate for Indicator Dial	onlinemetals.com	18149	14.11
Aluminum for Indicator Needle Bracket	onlinemetals.com	1178	2.14
Round Steel Tubing 1.0 in, .120 thick	onlinemetals.com	7776	3.09
Steel Strap 0.75 in wide, 1/8 in thick	onlinemetals.com	9998	11.47
Square Tubing 1.25x1.25, .120 thick	onlinemetals.com	10318	15.27
Total			$435.71

single testing machine. For example, the price of the plywood listed is only the portion needed to make the machine base, rather than the price of an entire 4 ft x 8 ft sheet.

5 Implementation

In the classroom this device was put to the test by having students perform torsional testing, and compile their results into a lab report. The undergraduate mechanics of materials course in which this device was used is the first in a series of engineering laboratory courses that students in the engineering program are required to take. Since it is the first in this series, it is used to teach students how to prepare formal lab reports. This is accomplished by introducing one section of the lab report each week, and having students focus primarily on that section, and writing the full details of that section (individually). Eventually, after each section of separate reports have been completed, students prepare a full lab report for one lab, incorporating all sections of the paper. The torsion-testing experiment is used to teach students how to write the "Method" section of their lab reports, and as explained, represents only one out of a series of twelve to fourteen experiments (depending on the semester). Compared to previous semesters, in which a much more complicated custom torsion-testing device was used, we found this device to be much faster and easier to operate, and student descriptions of the experimental setup were also more comprehensible, perhaps due to the simplifications afforded by this system. Students also had more time to work on report-writing activities since having multiple devices allowed students to all perform the experiments concurrently rather than waiting for equipment to become available.

In terms of accuracy, it is important for a device such as this to be accurate enough to get a reasonable measurement of values, but it is not necessary to be overly accurate, since students are learning the basic concepts of material behavior and testing, not certifying material properties. As mentioned previously, we estimated results to be within approximately 10% of published values. Tables 2, 3, and 4 provide sample data, collected by students, along with estimates of G.

Table 2: Sample torsion testing data for aluminum

Sample	Class	ϕ (deg)	T (lb $\cdot$ ft)	L (in)	d(in)	$G\,\frac{\text{lb}}{\text{in}^2}\cdot 10^6$
1	Su 21	9.50	15.12	23.06	0.50	4.179
2	Su 21	12.00	21.03	22.75	0.50	4.467
3	F 21	12.00	20.00	23.00	0.50	4.194
4	S 22	12.00	21.70	22.60	0.50	4.579
5	S 22	13.00	21.80	23.00	0.50	4.322
6	S 22	13.40	20.70	23.00	0.50	3.981
7	S 22	12.00	20.20	22.90	0.50	4.319
8	S 22	11.50	20.50	23.00	0.50	4.594
9	S 22	12.50	19.60	23.00	0.51	3.883
10	S 22	9.00	14.90	22.50	0.51	3.979
11	S 22	10.00	15.80	22.80	0.50	4.037
12	S 22	9.00	15.80	22.90	0.50	4.469
13	S 22	13.00	22.00	23.00	0.50	4.361
14	S 22	12.00	21.10	22.50	0.50	4.433
15	F 22	14.50	20.59	23.00	0.50	3.689
16	F 22	12.00	20.73	22.75	0.50	4.404
17	F 22	12.50	22.28	22.00	0.50	4.394
18	F 22	12.50	19.55	23.00	0.50	3.967
19	F 22	9.00	15.12	22.88	0.50	4.272
20	F 22	9.00	21.18	22.38	0.50	5.761
21	F 22	11.50	18.81	23.06	0.50	4.227
22	F 22	9.00	20.59	22.88	0.50	5.864
23	S 23	9.50	14.83	23.06	0.50	4.034
24	S 23	8.00	14.61	23.00	0.51	4.523
25	S 23	9.00	16.60	21.94	0.50	4.427
26	S 23	12.00	18.60	22.75	0.50	3.951
27	S 23	14.00	21.69	23.25	0.50	4.036
28	S 23	7.50	11.90	22.88	0.50	4.067
29	S 23	11.00	18.96	22.88	0.50	4.418
30	S 23	13.50	21.80	23.00	0.50	4.031
31	S 23	9.00	15.42	23.06	0.51	4.255
Mean		11.11	18.82	22.83	0.50	4.326
SD		1.914	2.897	0.299	0.002	0.457

Table 3: Sample torsion testing data for copper

Sample	Class	ϕ (deg)	T (lb $\cdot$ ft)	L (in)	d(in)	$G \frac{\text{lb}}{\text{in}^2} \cdot 10^6$
1	Su 21	7.50	20.36	22.88	0.50	7.071
2	Su 21	7.00	18.96	23.00	0.50	6.981
3	F 21	9.50	19.70	23.00	0.50	5.475
4	S 22	7.50	19.00	22.80	0.51	6.220
5	S 22	9.50	21.20	23.00	0.50	5.705
6	S 22	8.10	19.80	23.00	0.50	6.300
7	S 22	8.00	20.10	23.00	0.50	6.424
8	S 22	9.00	20.60	23.00	0.50	5.899
9	S 22	8.00	19.60	23.00	0.50	6.314
10	S 22	6.00	14.80	22.50	0.50	6.072
11	S 22	8.50	20.80	22.80	0.50	6.202
12	S 22	6.00	14.90	23.10	0.50	6.428
13	S 22	9.00	20.80	22.90	0.50	5.883
14	S 22	7.00	20.60	23.00	0.50	7.524
15	F 22	7.00	18.15	23.00	0.50	6.790
16	F 22	9.00	20.59	22.80	0.50	5.845
17	F 22	11.20	20.85	23.03	0.50	4.961
18	F 22	7.10	17.56	23.00	0.50	6.323
19	F 22	6.50	18.15	22.00	0.50	6.884
20	F 22	8.00	20.22	22.38	0.50	6.337
21	F 22	8.75	20.59	23.06	0.50	6.009
22	F 22	8.00	20.59	22.94	0.50	6.615
23	S 23	6.00	13.57	23.06	0.50	5.845
24	S 23	3.50	9.66	23.00	0.50	7.057
25	S 23	3.75	10.84	22.19	0.50	7.303
26	S 23	4.75	11.95	22.75	0.50	6.413
27	S 23	4.70	9.60	23.25	0.50	5.321
28	S 23	6.00	11.50	22.88	0.50	4.913
29	S 23	7.00	13.69	22.88	0.50	5.013
30	S 23	7.50	17.90	23.00	0.50	6.250
31	S 23	9.00	21.95	23.06	0.51	6.057
Mean		7.37	17.70	22.88	0.50	6.207
SD		1.739	3.806	0.269	0.002	0.656

Table 4: Sample torsion testing data for steel

Sample	Class	ϕ (deg)	T (lb $\cdot$ ft)	L (in)	d(in)	$G \frac{\text{lb}}{\text{in}^2} \cdot 10^6$
1	Su 21	5.00	21.10	23.00	0.50	10.619
2	Su 21	3.50	21.18	23.00	0.50	15.596
3	F 21	5.40	20.81	23.00	0.50	10.174
4	S 22	3.50	20.70	22.60	0.50	15.219
5	S 22	4.00	20.10	23.00	0.50	12.847
6	S 22	4.10	19.00	23.00	0.50	11.943
7	S 22	4.00	19.10	22.90	0.50	12.253
8	S 22	4.00	21.10	23.00	0.50	13.595
9	S 22	4.40	19.30	23.00	0.50	11.305
10	S 22	2.50	12.80	22.50	0.51	12.405
11	S 22	2.50	15.10	22.80	0.50	15.431
12	S 22	4.00	20.40	23.10	0.50	13.201
13	S 22	4.50	19.50	23.00	0.50	11.258
14	S 22	4.50	21.40	22.40	0.50	11.936
15	S 22	4.50	19.30	22.90	0.50	11.005
16	F 22	3.50	15.12	23.00	0.50	11.134
17	F 22	5.00	20.83	22.75	0.50	10.620
18	F 22	4.00	20.36	23.25	0.50	13.051
19	F 22	3.50	18.37	23.00	0.50	14.082
20	F 22	4.00	19.18	22.00	0.50	11.820
21	F 22	4.00	19.55	22.38	0.50	12.254
22	F 22	4.25	19.18	23.13	0.50	11.694
23	F 22	3.00	18.22	22.94	0.50	15.610
24	S 23	3.00	12.61	23.06	0.50	10.862
25	S 23	3.00	14.76	23.00	0.50	12.579
26	S 23	4.00	20.95	22.19	0.50	13.339
27	S 23	5.50	22.70	22.75	0.50	10.438
28	S 23	4.90	20.66	23.25	0.50	10.985
29	S 23	2.90	13.80	22.88	0.50	12.197
30	S 23	4.00	18.37	22.88	0.50	11.772
31	S 23	3.00	17.40	23.00	0.50	15.189
32	S 23	8.50	32.32	23.06	0.51	9.443
Mean		4.08	19.23	22.87	0.50	12.370
SD		1.118	3.543	0.291	0.002	1.684

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