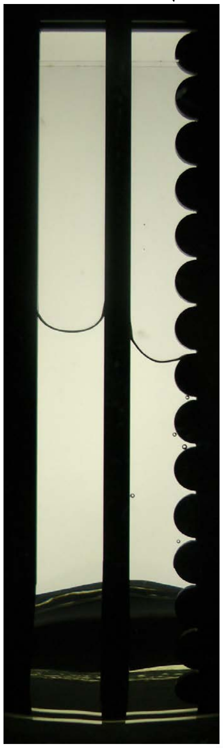
CELERE
Capillary Effects on Liquids Exploratory Research Experiments
Dennis Stocker

I-STEM Education *in Practice*

International Space Station Design Challenge

WHAT? The design challenge is a joint educational program of NASA and Portland State University (PSU) that enables students to participate in microgravity research on capillary action related to that conducted on the International Space Station (ISS). Students create their own experiments using Computer-Aided Design (CAD) with a provided template and tutorial for DraftSight software, which can be downloaded for free. Experiment proposals, each of which consists of a single CAD drawing and short entry form, are emailed to NASA. The test cells are then manufactured by PSU using the drawings and a computer-controlled laser cutter. Each experiment is conducted in PSU's Dryden Drop Tower, in which it falls 22 meters (73 feet) and experiences 2.1 seconds of apparent near weightlessness, i.e., microgravity. Video and still images from each drop are provided online for student analysis and the reporting of results, for example in a science fair or class presentation. The above right shows an example experiment (from Columbus, GA) during the middle of the drop, where the oil's upward motion is clearly slowed by the scalloped channel wall (in the right channel).



WHO? The design challenge is for students in Grades 8-12, who may participate as individuals or in teams of any size. Teams may include younger students as long as there is at least one team member in Grades 8-12, where this option can facilitate the participation of informal science clubs, scouts, etc. The program is limited to students from the United States, but is open to all fifty states, the District of Columbia, Puerto Rico, American Samoa, Guam, the Northern Mariana Islands, the U.S. Virgin Islands, and all DODEA schools for the children of U.S. military personnel (i.e., schools of the U.S. Department of Defense Education Activity). Citizenship is not required. Youth are free to get help from adults, for example in creating a CAD drawing.

WHEN? The drop tests will be conducted in three sets in early 2016, where the experiment proposals are submitted by email to celere@lists.nasa.gov by the first of February, March, and April; choose one—where early submission is best. Selected experiments are typically conducted during the month of the submission deadline.

WHERE? Students participate remotely, without travelling to PSU or NASA. But they can interact with NASA by email, teleconferencing, or video conferencing.

WHY? The design challenge enables students to learn about computer technology and participate in research related to space station science, both of which can inspire the pursuit of STEM careers. Boy Scouts could use the CAD drawing toward completion of the drafting merit badge. And selection in a nationwide NASA design challenge is an accomplishment worth noting on college applications!

CAPILLARY ACTION? Capillary action occurs when liquid molecules are more attracted to a surface than to each other. In paper towels, the water molecules move along tiny fibers. In plants (like celery), the water moves upward through narrow tubes called capillaries. Capillary action occurs on Earth, but can be difficult to observe—except with small capillaries—because of gravity. But when experiments fall in a drop tower, capillary effects are easy to see and study!

DROP TOWER? When an experiment falls down PSU's Dryden Drop Tower (shown above), it behaves as if gravity has nearly vanished—of course neglecting the fall! Our sensation of gravity and weight comes from a resistance to its pull, for example because of the floor holding us up. While freely falling, we feel weightless and that is the basis for many amusement park rides. This works because all objects fall at the same acceleration unless acted upon by another force. As one result, the astronauts and the ISS fall together (around the Earth) such that the astronauts float within the space station. This happens even though the space station is so close to the Earth that the gravity is only about 10% less than that on the planet's surface.

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Astronauts who've worked on CFE (for example) include Joe Acaba, Clay Anderson, Dan Burbank, Chris Cassidy, Cady Coleman, Tracy Caldwell Dyson, Mike Fincke, Kevin Ford, Mike Fossum, Mike Hopkins, Scott Kelly, Mike Lopez-Alegria, Bill McArthur, Tom Marshburn, Karen Nyberg, Don Pettit, Shannon Walker, Peggy Whitson, Jeff Williams, and Sunita Williams (seen above operating CFE).

PSU? Prof. Mark Weislogel of the Portland State University (PSU) is a world leader in the study of capillary action and with NASA support has had such experiments conducted in drop towers, on the space shuttle, on the Russian *Mir* space station, and on the International Space Station (ISS). His ISS research has included both the Capillary Channel Flow (CCF) experiment and the Capillary Flow Experiment (CFE).

SELECTION? Thus far, 100% of the proposals received have been selected for fabrication and testing because of the limited number of entries received for this new program. While that might not continue in 2016, the plan is to select up to 100 entries from across the nation. Selection of at least one qualifying 2016 entry from each state and territory (listed under *WHO?*) is guaranteed. Only eight states have had participants to date, so the odds of selection are very high! See the 2016 handbook for more information about selection.

QUESTIONS? See http://spaceflightsystems.grc.nasa.gov/CELERE/ or email celere@lists.nasa.gov.

One Team's Final Report:

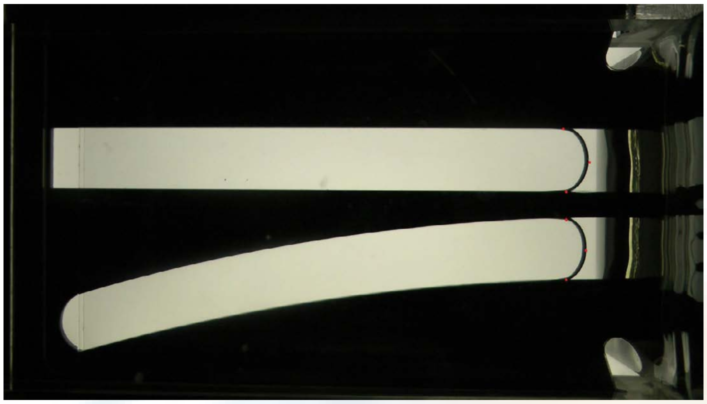
State: Georgia
Organization: Columbus High School
Team Name: CELERE Squadron
Students' Grade Level: 12th
Students on Team (7): Thomas Harris, Mary Catharine Martin, Alexander Nordin, Kishan Pithadia,
Aaron Sommer, Tobore Tasker, Kelsey Tjen
Adult Advisor: Mr. Luther Richardson, Physics Teacher

EXPERIMENT INFORMATION

Flow Rate Investigation Due to Basic Physics Effects

Method of Analysis

Looking at each frame from the video, we used Paint to find six points of data for each frame—where the silicon liquid level touches the tube on the left and right and the liquid level in the middle of the tube for each of the two tubes (the control and the variable). Each point has two coordinates, which we then combined to find an R value ($\sqrt{x^2 + y^2}$), or the distance from (0,0) on the screen. Knowing that the frame rate for these videos is 59 frames per second, we then converted the frame number into seconds. We also know that the straight tube is 17 mm x 184 mm,



Example of the points collected on each frame (6 points in red).
Each point has an x and y coordinate.

and could then convert pixels to millimeters. The change in mm over the change in time is velocity. We then created multiple plots showing the progression of the silicon liquid through the tube over time, as well as different velocities. These graphs were fitted with lines of best-fit and are analyzed below. In all trials, the graphs of X coordinates versus time were all fit with a linear trend line; and it is interesting to note that the data tapers off towards the end, as though approaching a horizontal asymptote.

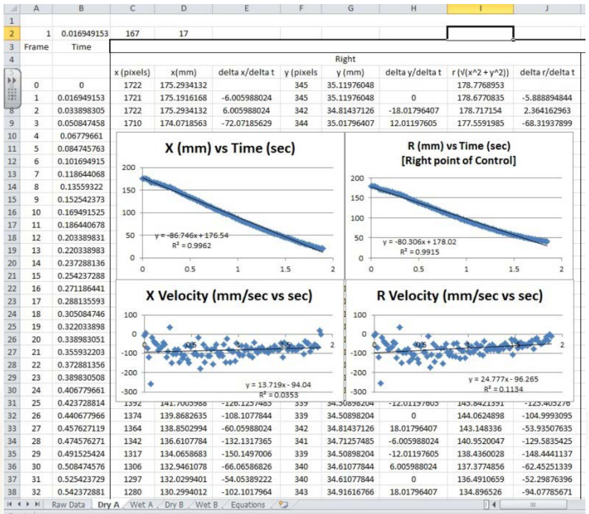
Analysis:

Dry A - http://celere.mme.pdx.edu/CELERE_2013/CELERE_2013_GA_CHS_Richardson_A/

This trial featured a curved path and a straight path. Just by watching the video, it seems as if the silicon liquid travels at similar horizontal velocities through both paths. In other words, the silicon liquid seems to be traveling at a constant and equal rate in each tube. The difference between the times that the silicon liquid reaches the end of the tubes is barely noticeable, though there is a difference. The silicon liquid seems to reach the end of the curved tube first, which contradicts our expectations.

Looking at the graphs of the R Velocities versus Time, we can see that the velocities are largely linear and approach zero, indicating that the silicon liquid level in the tubes approach the top more slowly as time passes. In both tubes, the velocity of the silicon liquid level in the middle of the tube is noticeably smaller than either of the side velocities, showing that the silicon liquid creeps up the side of the tube faster than the middle is forced upwards due to capillary action.

In the curved tube, the acceleration of the right side of the liquid (derivative of velocity equations) was also distinctly larger than the acceleration of the left side, which accounts for why the liquid reached the same points normal to the sides of the tube at the same time. This is attributed to the normal force in the tubes. The overall velocities for the curved tube are distinctly larger than the velocities in the straight tube, which supports the video that shows the silicon liquid reaching the end of the curved tube first. A possible reason for this effect is the normal force created as a result of the curved tube.



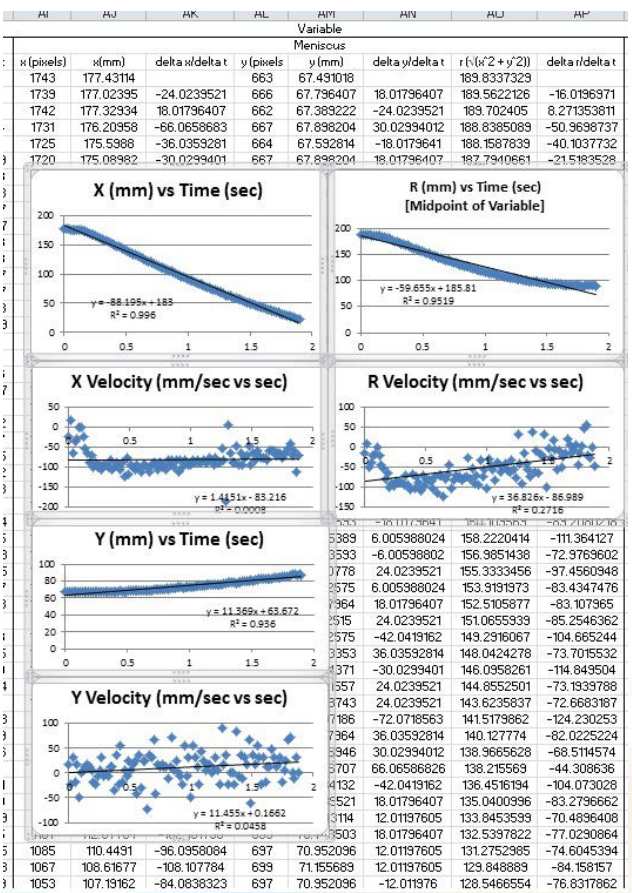
Example of data sheet and plotted data for Dry A trial, right point of control.

Wet A - http://celere.mme.pdx.edu/CELERE_2013/CELERE_2013_GA_CHS_Richardson_A/

This trial included a curved path and a straight path, and the tubes had already been dropped once. This second trial's purpose was to see if the silicon liquid from the previous trial would affect the silicon liquid's cohesion to the rest of the silicon liquid and the adhesion to the side of the tubes. The distance travelled by silicon liquid through the center of each tube was the same, so the two droplets of silicon liquid should have reached the end of the paths at approximately the same time. But, since one path was curved, the capillary force may have been slightly different which would change the normal force, which would cause friction to change. In the video, the silicon liquid droplet in the curved tube reaches the end just moments before the droplet in the straight tube, once again contradicting our predictions.

Just as in the dry trial, the overall velocities for the curved tube are higher than the ones for the straight tube, indicating that the silicon liquid level accelerated more in the curved tube.
The effects of a slick surface as opposed to the dry surface in trial Dry A do not seem significant, and the graphs of the wet trial match the graphs of the dry trial very closely.

The R Velocity data points follow a clearer linear trend in the curved tube than in the straight tube, where the data points are more scattered and random. This visual observation is supported by the R2 values on each graph, which show the correlation of the data points to the trend line. This shows that the velocity in the curved tube is more linear (and the acceleration is more constant).



Example of data sheet and plotted graphs for midpoint of variable in Wet A trial.

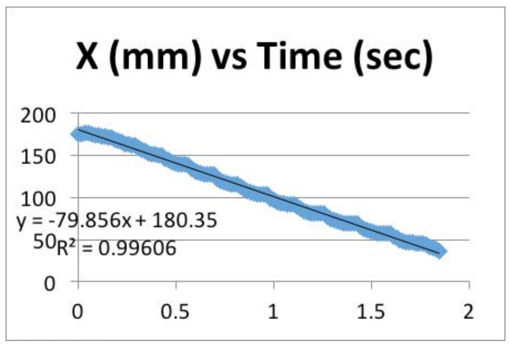
For the B trials, we paid less attention to the y values of the data points because they did not significantly affect the data.

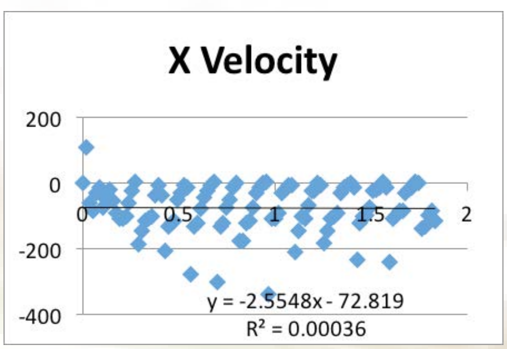
Dry B - http://celere.mme.pdx.edu/CELERE_2013/CELERE_2013_GA_CHS_Richardson_B/

In this trial, the right tube had its right side indented with hemispheres, and the left side was straight, while the left tube was the control: a right cylinder. The right tube at its narrowest point was as wide as the left tube; therefore we concluded that the left tube's silicon liquid level would increase faster than that of the right tube. While this hypothesis was experimentally verified with a significant distance, the right tube's left (straight) side became submerged faster than the right indented side(but slower than the left tube) because of the silicon liquid's capillary action on the sides of the tube: the adhesive forces on the left side pulled the silicon liquid up, while the forces on the right side pulled the edge anywhere in an 180 degree angle, corresponding to the section of the hemisphere that it currently touched.

The graphs of the X velocities on the variable tube's right side seem to resemble sinusoidal functions, which may result from the indentations in the position graphs. These indentations cause the position graphs to appear as slanted sinusoidal functions with extremely small periods and amplitudes. A peak in each "bump" of the position function occurs quite regularly (every 3-4 time intervals), and the velocity graph increases during that period. At the peak, the velocity seems to "reset," dropping down to a negative velocity and starting to climb back up until the next bump. These bumps correspond to the wedges between the semicircles, showing how the wedge affects velocity.

Looking once again at the overall velocities and accelerations of the liquid, the equations show that the straight tube has greater velocities and accelerations. This supports the observation that the liquid level both flowed faster and increased faster in the straight tube than in the wedged tube. It was also obvious that the wedges slowed down the liquid's flow. The presence of gas bubbles is notable, but such small bubbles have little to no effect on the liquid's flow rate.





Wet B - http://celere.mme.pdx.edu/CELERE_2013/CELERE_2013_GA_CHS_Richardson_B/

This trial featured two tubes: one straight tube with no special changes that acts as the control and one straight tube with circular bumps of equal radii on one side. During the drop, the silicon liquid level in the control tube ascended at a generally constant rate. The silicon liquid level in the experimental tube also ascended at a constant rate, but it ascended more slowly than that in the control tube. The silicon liquid level on straight side on the experimental tube ascended close to but still slightly behind the level in the control, but the level on the bumpy side of the experimental lagged behind by a large amount. Bubbles were produced on the bumpy side as the silicon liquid level passed each of the indentions.

Just as in the dry trial, the liquid on the bumpy side has a much smaller velocity and acceleration at every point along the tube than either the smooth side of the same tube or either side of the straight tube.
The overall plots of the data match the plots of the dry trial, however the accelerations for the sides seem larger in the wet trial, but the midpoints have smaller accelerations. This shows the effect of capillary action and cohesion as the sides of the tubes were already slick from the previous trial.

		X vs Time	X Velocity	R vs Time	R Velocity
Dry B Variable	Right	y = -79.748x + 179.72	y = -2.2757x - 73.35	y = -73.539x + 182.55	y = 8.2882x - 75.724
	Middle	y = -79.856x + 180.35	y = -2.5548x - 72.819	y = -73.424x + 183.68	y = 14.344x - 79.555
	Left	y = -81.225x + 174.59	y = 7.0404x - 84.632	y = -69.904x + 179.58	y = 21.768x - 85.656
Dry B Control	Right	y = -88.606x + 176.77	y = 5.4347x - 88.562	y = -71.87x + 181.99	y = 27.275x - 90.573
	Middle	y = -88.528x + 180.49	y = 0.8177x - 83.179	y = -70.228x + 188.06	y = 22.633x - 83.752
	Left	y = -88.572x + 176.32	y = 6.7515x - 89.602	y = -66.012x + 186.61	y = 30.178x - 87.89
Wet B Variable	Right	y = -78.584x + 179.9	y = -5.4839x - 68.816	y = -72.919x + 182.5	y = 4.7098x - 71.23
	Middle	y = -79.495x + 179.76	y = 3.0638x - 76.419	y = -71.874x + 183.42	y = 10.933x - 76.098
	Left	y = -81.124x + 171.66	y = 13.47x - 90.957	y = -69.503x + 176.26	y = 27.672x - 91.371
Wet B Control	Right	y = -84.822x + 171.14	y = 15.516x - 96.466	y = -69.024x + 176.71	y = 34.339x - 96.903
	Middle	y = -87.412x + 181.12	y = -0.023x - 80.757	y = -69.861x + 188.8	y = 18.718x - 80.092
	Left	y = -85.879x + 173.37	y = 10.163x - 91.623	y = -64.279x + 183.8	y = 31.497x - 89.048

Equations of best-fit lines for Wet B and Dry B trials.

For more information, please see:
http://columbusphysics.wikispaces.com/CELERE+Final+Report