DOCUMENT RESUME

ED 439 965 SE 063 489

AUTHOR	Baroway, William
TITLE	Construct-a-Boat. Science by Design Series.
INSTITUTION	TERC, Cambridge, MA.; National Science Teachers Association, Arlington, VA.
SPONS AGENCY	National Science Foundation, Arlington, VA.
ISBN	ISBN-0-87355-178-8
PUB DATE	2000-03-00
NOTE	107p.; For other books in the Science by Design Series, see SE 063 488-491.
CONTRACT	ESI-9252894; ESI-9550540
AVAILABLE FROM	NSTA Press, 1840 Wilson Blvd., Arlington, VA 22201-3000. Web site: http://www.nsta.org.
PUB TYPE	Books (010) -- Guides - Classroom - Teacher (052)
EDRS PRICE	MF01/PC05 Plus Postage.
DESCRIPTORS	*Construction (Process); *Design; High Schools; Maritime Education; Physics; Problem Solving; Research Methodology; *Resource Materials; *Science Activities; Teaching Methods; Technology
IDENTIFIERS	*Boats

ABSTRACT

This book is one of four books in the Science-by-Design Series created by TERC and funded by the National Science Foundation (NSF). It challenges high school students to investigate the physics of boat performance and work with systems and modeling. Through research, design, testing, and evaluation of a model boat, students experience the practical application of mass, speed, and acceleration while applying the math and science necessary to build a scale model. The activities have assessment suggestions and Internet extensions through the National Science Teachers Association's (NSTA) sciLINKS program and are designed to meet the new International Technology Education Standards as well as the National Science Education Standards. Key ideas include: (1) "Forces, Speed, and Acceleration"--as they seek to meet the design specifications of the boat, students learn about mass, speed, acceleration, and forces through practical application of these concepts. Students investigate the relationships among these variables through qualitative observation and quantitative measurement of changes and rates of change in each variable; (2) "Systems"--students work with variables to study system behavior and learn to construct the feedback loops that determine the limits of model boat performance; (3) "Modeling"--students apply the science and math necessary to build an accurate scale model and extend this analysis to computer modeling. Homework and class assignments guide students through problem-solving in algebra, plane and solid geometry, and making connections to other disciplines; and (4) "Inquiry and Design"--students undertake inquiry and design as iterative, multi-disciplinary processes through which to develop abilities in identifying, creating, investigating, decision-making, building, testing, and evaluating. Appendices contain inquiry and design processes, text reconstruction, and sample answers. (Contains a glossary and 26 references.) (CCM)

boat

by Design

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Construct-a-Boat

Developed by TERC
Lead author: William Baroway

This curriculum was developed by TERC,
Cambridge, Massachusetts. Funded in part
by a grant from the National Science
Foundation.

T E R C

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Science by Design: Construct-a-Boat
Library of Congress Catalog Card Number 00-131680
NSTA Stock Number: PB152X2
ISBN 0-87355-178-8
Printed in the United States of America by Automated Graphic Systems, Inc.
Printed on recycled paper

This book was prepared with the support of the National Science Foundation under Grant Nos. ESI-9252894 and ESI-9550540. However, any opinions, findings, conclusions, and/or recommendations herein are those of the authors and do not necessarily reflect the views of the National Science Foundation.

National Science Teachers Association

TERC

Acknowledgments

The creation of the NSTA *Science by Design* series builds on five years of research and development at TERC. This work was funded by two National Science Foundation grants: ESI-9252894 and ESI-9550540 and was directed by John Foster, David Crismond, William Barowy, and Jack Lochhead.

We are especially grateful for the vision, guidance, and prodding of our program officer, Gerhard Salinger, who was our GPS in uncharted territory.

We were helped in innumerable ways by an especially insightful advisory board: Joan Baron, Goery Delacote, Andy DiSessa, Woodie Flowers, John Foster, Mike Hacker, Colleen Hill, Gretchen Kalonji, Robert McCormick, Jim Minstrell, Jim Neujahr, and David Perkins.

The members of the TERC team who contributed to the development and testing of the *Science by Design* units include:

Tim Barclay
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Tasha Morris
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Alison Paddock
Meghan Pfister
Lee Pulis
Jerry Touger
Margaret Vickers
Paul Wagoner
Kelly Wedding
Amy Weinberg

Special mention must be made of the enthusiasm, dedication, and long hours contributed by David Crismond and Earl Carlyon. The following hard-working consultants added greatly to our efforts: Hilton Abbott, Robert B. Angus, Carol Ascher, Warren R. Atkinson, Earl Carlyon, Michael Clarage, Jan Hawkins, Kathy Kittredge, Crispin Miller, James E. LaPorte, Kjell-Jan Rye, Rick Satchwell, Mike Stevens, and Ron Todd.

The authors of the final *Science by Design* units were William Barowy, Felicia Lee, Jack Lochhead, Alison Paddock, and Lee Pulis of TERC.

Science by Design: Construct-a-Boat was produced by NSTA Press: Shirley Watt Ireton, director; Beth Daniels, managing editor; Erin Miller, associate editor; Jessica Green, assistant editor; Michelle Treistman, assistant editor; Anne Early, editorial assistant. Beth Daniels was project editor for the *Science by Design* series. The cover design and book design are by Camden Frost and Vicky Robinson of Graves Fowler Associates.

Field testing of the *Science by Design* series depended on the dedication of dozens of teachers and the helpful cooperation of their school systems:

Jerian Abel, Northwest Regional Education Laboratory
Bruce Andersen, Buker Middle School
Dave Armstrong, Lawrence Middle School
Henry Bachand, Mansfield High School
Hilda Bachrach, Dana Hall School
Ronald Bjorklund, Leicester High School
Marcella Boyd, Manchester Junior High School
Karen Bouffard, Governor Dummer Academy
Althea Brown, Medford High School
Lee Burgess, Lawrence Middle School
David Corbett, Whittier Regional Vocational Technical High School
Steve Cremer, Braintree High School
Deborah Crough, Long Beach High School
Ron Daddario, McCall Middle School
Raymond P. Gaynor, Reid Middle School
Elizabeth George, Westborough High School
Pam Glass, Talbot Middle School
Rick Harwood, Ware High School
Gary Herl, Tantasqua Regional Junior High School
Kate Hibbitt, Lincoln School
Patrick Keleher, Norwood Junior High School
Marty Kibby, Minetron Technology Education Office
Matias Kvaternik, Chelmsford Public Charter School
Jeff Leonard, F.A. Day Middle School
Walter Lewandowsler, Bartlett High School
David R. Littlewood, Agawam Junior High School
John Matthews, Southwick Tolland Regional High School
Eilen McCormack, South Jr. High Brockton
Scott McDonald, Needham High School
Brian McGee, Lexington Middle School
Bob Meltz, Manchester Junior-Senior High School
Charles O'Reilly, Lexington High School
Constance Patten, Lincoln-Sudbury High School
Fred Perrone, East Junior High School
Joe Pignatiello, Somerville High School
Doug Prime, Lancaster Middle School
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Thomas Rosa, Walsh Middle School
Eugene A. Santoro, Silver Lake Regional High School
John Schott, Smith Academy
Bruce Seiger, Wellesley High School
Douglas Somerville, Woodword Middle School
John Stamp, Manchester High School
Mike Stevens, Maynard High School
Michael Sylvia, Charles E. Brown Middle School
Syd Taylor, Mahar Regional School
Ted Vining, Monument Regional High School
Frank Viscardi, Framingham High School

This project would not have been possible without the help and critique of hundreds of students whom we regretfully cannot mention by name.

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A NOTE FROM THE DEVELOPERS

Integrating Science and Technology

Construct-a-Boat is aligned with the *National Science Education Standards* for process and content standards in both physical science and mathematics. This alignment is illustrated on pages four and five. Through inquiry and design, students develop conceptual understanding of electromechanical energy transfer, friction, and mathematical modeling. Because design activities motivate inquiry, and inquiry informs design, students engage in the iterative processes of scientific inquiry and technological design through a variety of hands-on activities.

Compare these materials to a highway: if you rush straight through, your students will learn only a little about the territory they have crossed. We provide a number of interesting side roads, which offer additional opportunities to investigate the linkage of inquiry and design. For your first trip, you may want to stay close to the highway, but as you gain experience, we hope you will drift further and further from it.

Schedule and Cost

The minimum time needed to complete the core unit is about 14–19 class sessions. More time will be needed if you choose to extend the unit either by undertaking a more advanced design and fabrication process, or by pursuing more advanced treatment of mathematical modeling.

Working in teams, students make a Quick-Build model boat using the *Design Brief* challenge and instructions for (about three class sessions). During the research and development phases (8–12 class sessions), students take baseline measurements, identify relevant variables, design and conduct experiments, study the model boat system, propose conceptual models, and generate possible solutions to their design problems. Students develop designs, build the models, conduct further investigations, analyze their data, and redesign their models if necessary. The unit concludes with student presentations of products, including supporting scientific arguments (three–four class periods).

We suggest that you impose a very low cost limit on materials ($1 to $2 per student) and encourage the use of recycled materials.

Construct-a-Boat works well in a physical science, technology, or mathematics course. You may wish to coordinate instruction of relevant topics with teachers of other courses.

KEY IDEAS

Forces, Speed, and Acceleration

As they seek to meet the design specifications of the boat, students learn about mass, speed, acceleration, and forces through practical application of these concepts. Students investigate the relationships among these variables through qualitative observation and quantitative measurement of changes and rates of change in each variable.

Systems

Students work with variables to study system behavior. They learn to construct the feedback loops that determine the limits of model boat performance.

Modeling

Students apply the science and math necessary to build an accurate scale model, and extend this analysis to computer modeling. Homework and class assignments guide students through problem-solving in algebra, plane and solid geometry, and show students how to make connections to other disciplines.

Inquiry and Design

Students undertake inquiry and design as iterative, multi-disciplinary processes through which students develop abilities in identifying, creating, investigating, decision-making, building, testing, and evaluating. These process cycles are outlined for teacher comment and student review in the resource readings in Appendix TBD.

Inquiry includes designing and conducting investigations; recognizing and applying models; constructing explanations; making predictions; and evaluating explanations. Because the focus of *Construct-a-Boat* is on the design-and-build process, students develop conceptual, mathematical, and computer models with structured guidance, and apply expert-built models to the making of a scale model.

Design includes research, testing, and constructing evaluation feedback loops as part of the design cycle. A reading on the history of boat building provides context for the technological design background given to the students in this unit.

ASSESSMENT

Student activity sheets may be used for formative or summative assessment. The first *Snapshot of Understanding* is intended as a pre-learning index of prior knowledge. It may be compared to similar answers on the final *Snapshot* given at the end of the last activity, for student self-assessment of learning. Because group work is stressed throughout the unit, group assessment may prove to be more appropriate than individual scores. However, depending on your class objectives, homework assignments may provide the best measure of individual performance.

Portfolio Suggestions

A portfolio can be a useful tool for maintaining individual accountability in a teamwork environment, because in a portfolio, students can capture representative samples of their work done over time. One resource among the many guides to portfolio assessment is:

Portfolio Assessment: A Handbook for Educators by James Barton and Angelo Collins, Addison-Wesley, 1997.

Potential Portfolio Items

The following set of items and products can be accumulated in portfolios for summative assessment. Each corresponds to a core or enrichment activity outlined in the Activities Overview schematic on page six. They are (with handouts printed in italics):

- Initial questions: *Design Brief*
- Individual information search
- Sketch of boat hull design
- Brainstorming record
- List of variables
- Research and results
- Group process description: *The Inquiry Process*
- Group process description: *The Design Process*
- Prototype demonstration notes
- Group summary documentation: *Product Prospectus*
- Post-test and self-assessment: *Snapshot of Understanding*

Standards and Benchmarks Connections

TASK	SOURCE
☐ *Students recognize the evolution of computer models and scale models in the shipbuilding industry and the impact of resulting performance improvement on the environment* **Standard/Benchmark:** Science, Technology & Society	NCSS VIII
☐ *Students recognize that systems have layers of controls* **Standard/Benchmark:** Design and Systems	AAAS 9–12
☐ *Students troubleshoot common mechanical and electrical systems, checking for possible causes of malfunction* **Standard/Benchmark:** Manipulation and Observation	AAAS 9–12
☐ *Students recognize the use of scale modeling for performance testing* **Standard/Benchmark:** Design and Systems	AAAS 9–12
☐ *Students use tools safely for construction* **Standard/Benchmark:** Manipulation and Observation	AAAS 9–12
☐ *Students identify and describe variables that affect the efficiency of the boat as a mechanical system.* **Standard/Benchmark:** Systems; Processes: Determining and Controlling Behavior of Technological Systems; Evidence, Models, and Explanation	AAAS 9–12, ITEA II, NSES K–12
☐ *Students interpret scale drawings, interpret and draw three-dimensional objects* **Standard/Benchmark:** Communication Skills; Geometry from a Synthetic Perspective	AAAS 9–12, NCTM 7
☐ *Students understand how things work and design solutions using systems analysis* **Standard/Benchmark:** Systems	AAAS 9–12
☐ *Students compare model predictions to observations and use computer models to explore the logical consequences of a set of instructions* **Standard/Benchmark:** Design and Systems; Information Processing	AAAS 9–12
☐ *Students recognize that different properties are affected to different degrees by changes in scale* **Standard/Benchmark:** Scale	AAAS 9–12
☐ *Students understand how mathematical modeling aids in technological design by simulating how a proposed system would theoretically behave; students recognize the limits of a mathematical model in how well it can represent how the world works* **Standard/Benchmark:** Symbolic Relationships; Mathematics as Problem Solving	AAAS 9–12, NCTM 1

TASK	SOURCE
☐ *Students recognize tables, graphs, and symbols as alternative ways to represent data and relationships that can be translated from one to another, and use computer for producing tables and graphs and for making spreadsheet calculations* **Standard/Benchmark:** Symbolic Relationships; Manipulation and Observation	AAAS 9–12
☐ *Students model real-world phenomena with a variety of functions, represent and analyze relationships using tables, verbal rules, equations, and graphs to translate among tabular, symbolic, and graphical representations of functions* **Standard/Benchmark:** Functions	NCTM 6
☐ *Students design and conduct a scientific investigation, formulate and revise scientific explanations and models using logic and evidence* **Standard/Benchmark:** Science as Inquiry	NSES 9–12
☐ *Students observe that objects change their motion only when a net force is applied* **Standard/Benchmark:** Physical Science	NSES 9–12
☐ *Students develop abilities of technological design including brainstorming design ideas, choosing among alternative solutions, implementing a proposed solution, and evaluating the solution and its consequences* **Standard/Benchmark:** Science and Technology	NSES 9–12
☐ *Students communicate the design problem, process, and solution, and write clear, step-by-step instructions for conducting investigations* **Standard/Benchmark:** Communication Skills; Science and Technology	AAAS 9–12, NSES 9–12
☐ *Students self-assess their learning by comparing pre- and post-Snapshots of Understanding* **Standard/Benchmark:** Issues in Technology; Science, Technology, and Society	AAAS 9–12, NCSS VIII

SOURCE KEY:

AAAS	American Association for the Advancement of Science. 1993. *Project 2061: Benchmarks for Science Literacy*. New York: Oxford University Press.
ITEA	International Technology Education Association. 1996. *Technology for All Americans: A Rationale and Structure for the Study of Technology.*
NCSS	Task Force on Social Studies Teacher Education Standards. 1997. *National Standards for Social Studies Teachers.* Washington, DC: National Council for the Social Studies.
NCTM	National Council for Teachers of Mathematics. 1991. *Professional Standards for Teaching Mathematics.* Reston, VA: NCTM.
NSES	National Research Council. 1996. *National Science Education Standards.* Washington DC: National Academy Press.

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Topic: acceleration
Code: CAB01

Topic: modeling
Code: CAB02

Topic: friction
Code: CAB03

Topic: presenting data
Code: CAB04

Topic: mass
Code: CAB05

Topic: force
Code: CAB06

Topic: buoyancy
Code: CAB07

Topic: scientific inquiry
Code: CAB08

Science by Design: Construct-a-Boat brings you *sci*LINKS, a new project that blends the two main delivery systems for curriculum—books and telecommunications—into a dynamic new educational tool for all children, their parents, and their teachers. This effort, called *sci*LINKS, links specific science content with instructionally rich Internet resources. *sci*LINKS represents an enormous opportunity to create new pathways to learners, new opportunities for professional growth among teachers, and new modes of engagement for parents.

In this *sci*LINKed text, you will find an icon near several of the concepts you are studying. Under it, you will find the *sci*LINKS URL (http://www.scilinks.org/) and a code. Go to the *sci*LINKS Web site, sign in, type the code from your text, and you will receive a list of URLs that are selected by science educators. Sites are chosen for accurate and age-appropriate content and good pedagogy. The underlying database changes constantly, eliminating dead or revised sites or simply replacing them with better selections. The ink may dry on the page, but the science it describes will always be fresh. *sci*LINKS also ensures that the online content teachers count on remains available for the life of this text. The *sci*LINKS search team regularly reviews the materials to which this text points—revising the URLs as needed or replacing Web pages that have disappeared with new pages. When you send your students to *sci*LINKS to use a code from this text, you can always count on good content being available.

The selection process involves four review stages:

1. First, a cadre of undergraduate science education majors searches the World Wide Web for interesting science resources. The undergraduates submit about 500 sites a week for consideration.
2. Next, packets of these Web pages are organized and sent to teacher-Webwatchers with expertise in given fields and grade levels. The teacher-Webwatchers can also submit Web pages that they have found on their own. The teachers pick the jewels from this selection and correlate them to the National Science Education Standards. These pages are submitted to the *sci*LINKS database.
3. Then scientists review these correlated sites for accuracy.
4. Finally, NSTA staff approve the Web pages and edit the information provided for accuracy and consistent style.

Course Outline

Design Brief
- *Model Boat Design Brief*
- *Snapshot of Understanding*
- *Scale Modeling at Work*

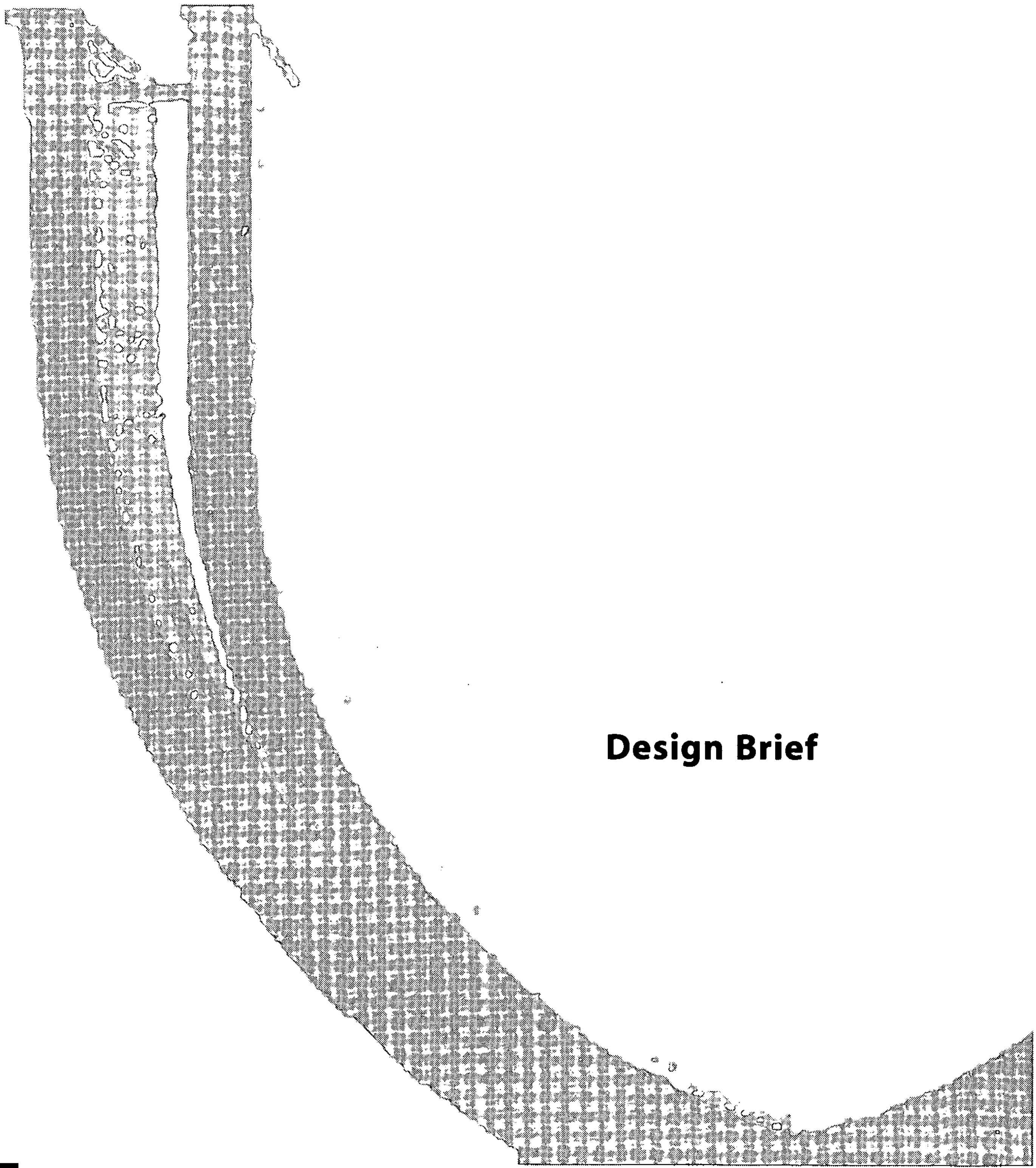
Quick-Build Model Boat
- *Quick-Build Specifications*
- *Blueprint*
- *Electrical Drawings*
- *Electrical Switch Detail Drawing*
- *Making the Test Tank*
- *Exploring the Model Boat System*
- *Systems Modeling*

Research
- Overview
- *Baseline Measurements*
- *Identifying Variables*
- Scale Model Preparation
  - *Homework*
  - *Application of Scaling*
  - *Scale Model Extension*
- *Fluid Friction Dynamics*
- *Minimizing Surface Area*

Development
- Overview
- *Designer Problem*
- *Builder Problem*
- *Prototype Construction*
- *Evaluating Design*

Communication
- Overview
- *Creating a Project Report*
- *Presentation*
- *Snapshot of Understanding*

Activity 1



Design Brief

MODEL BOAT DESIGN BRIEF

DAY 1

You are an employee of Quality Boat Systems (QBS), a company that designs boat hulls for carrying people and cars. Like many other boat design companies, QBS has been able to develop cost-effective, high-performance hulls by computer modeling and testing scale models. Your customers want boats that will speed up service. QBS scientists say that the way to do this is to maximize the boat's acceleration and its top speed. Your team's challenge is to research how to improve acceleration and top speed by redesigning the boat hull.

Scope of Work

- Make a Quick-Build according to plans and collect baseline performance data
- Identify and research key design features
- Redesign the model hull to improve performance
- Test the new design to calculate percent improvement in performance
- Document progress, design improvements and tests
- Write a report and present your work

If successful, your new design will perform better than the Quick-Build model.

Salespeople have determined that the QBS company can sell boats to customers with the following specifications similar to the M/V Nantucket:

Performance Specifications

Maximum top speed: 30 km/hr
Fuel consumption: ~350 liters/hr
Maximum acceleration: 0.1 m/sec^2
Power twin 3,000 horsepower turbine

Physical Specifications

Weight: 1170 metric tons
Beam: 18 meters
Passenger capacity: 1100 (including crew)
Length overall: 70 meters
Vehicle capacity: 60 mid-size cars

SNAPSHOT *of Understanding:*

What I already know about models, systems, and design.

The unit of study you are about to begin will challenge you to design, build, and test the performance of a model boat. To meet this challenge, you will have to investigate the physics of performance and the concepts of a model boat system. Before you begin, record a sampling of what you already know by answering the questions below. This is not a test; rather, it is a series of questions that ask about your current knowledge of key ideas in this unit. At the end of the unit, you will answer similar questions and compare what you have learned.

1. What are some of the factors that would have significant effects on the speed and acceleration of a model boat?

2. Do these factors have any effect on each other? If so, what might those effects be?

3. What are models used for?

4. What is a system?

5. Have you ever designed a project or built something with tools?

   If yes, describe your project and list your major process stages from concept to finish. If no, think about and list what steps you might go through to design and build a boat hull for higher performance.

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6. Describe an experiment that determines which of two boats has greater acceleration.

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Topic: modeling
Go to: www.scilinks.org
Code: CAB02

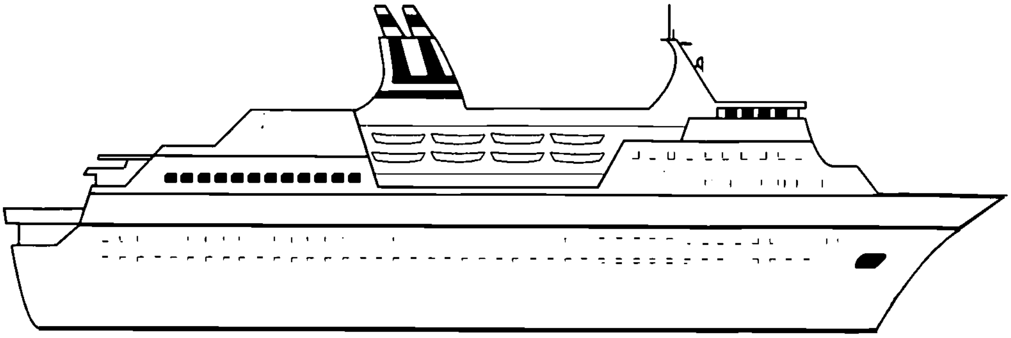
SCALE MODELING AT WORK: TESTING SHIP PERFORMANCE

In ship building, scale models are basically small versions of the ship that the designer wants to make. It is important that the model looks like the ship and *acts like the ship*. Ship designers often do their testing on models in order to develop cost-effective, high-performance ships. Testing is cheaper, less time-consuming, and safer when carried out on models rather than on full scale ships.

By placing the model in a test tank, designers can measure handling characteristics such as stability in heavy seas, resistance to forward motion, and power required to move at a certain speed.

Sometimes ship designers must build and test several models, particularly if they are working under strict requirements regarding speed, fuel cost, and the ship's effect on the environment. Years ago, one or two tests were enough to ensure that the actual ship would satisfy design requirements. Today, however, ship designers must find ways to lower fuel costs and reduce pollution from engines, so it has become more important to design efficient hulls. Designers often test models and make modifications many times for each design.

One measure of ship designers' success with models is how much they can reduce the cost of running a ship over a 20-year lifespan. It is not unusual to obtain a 10–15 percent improvement as a result of careful model testing. These gains can be obtained by making small changes in the shape and finish of the hull, the size of the propellers, or the power of the engine.



On new cruise liners, fuel costs have been reduced by 10–15 percent through model testing.

DAY 1

OVERVIEW—DESIGN BRIEF

Give students the *Design Brief* and the *Snapshot of Understanding.* Initiate class discussion and highlight important design issues.

Construct-a-Boat Challenge to Students

Each student, as a member of a product research and development team, is to research how to improve acceleration and top speed by redesigning a boat hull. If successful, the new design will perform better than the Quick-Build model.

SNAPSHOT of Understanding:

Working individually, students answer questions about their prior experience with modeling and with designing experiments.

Homework (optional): Students might read about the history of boat building to understand boat design as it has evolved from a craft to the highly developed computer modeling techniques of today.

TEACHING SUGGESTIONS

Introduction

Hand out the *Design Brief* student activity sheets. Ask students to keep these and future sheets together and to bring them to the classroom with other notes to serve as a record and reference for daily activity (and assessment) in the unit. Advise students that they will work in teams, use processes of technological design and scientific inquiry, and that other teams will critique their prototype with respect to the challenge criteria.

Students are also required to document their activity in a Lab Journal in order to contribute effectively to the final team presentation and to enhance their individual portfolios. Be clear on your rubrics for assessing work and share them with students. Indicate which activities will be individually graded and which will be given a team score. Be prepared to justify team scoring if some students (or parents) are not used to the idea.

If computer modeling, Computer Aided Design (CAD), or Computer Aided Modeling (CAM) activities will be involved, you may want to mention this at the beginning of the unit, but hold introduction of the equipment until a later class.

MATERIALS

Student Activity Sheets

- Course Outline
- Design Brief
- Snapshot of Understanding

Ring, Pocket, or Folio Binder

- *(student supplied) for keeping student activity sheets, notes, Lab Journal, and drawings for reference and portfolio*

PREPARATION

- *Read and become familiar with the entire unit.*
- *Define your assessment system with a clear, simple description.*
- *Locate optional homework readings. These should feature local boat building activities: traditional or contemporary.*

Pre-Assessment

Hand out the *Snapshot of Understanding*. Emphasize that it is not a test, and that students will not be graded on this activity. The purpose of the *Snapshot* is self-diagnostic—to find out what students know initially about the key science and technology learning objectives of *Construct-a-Boat*.

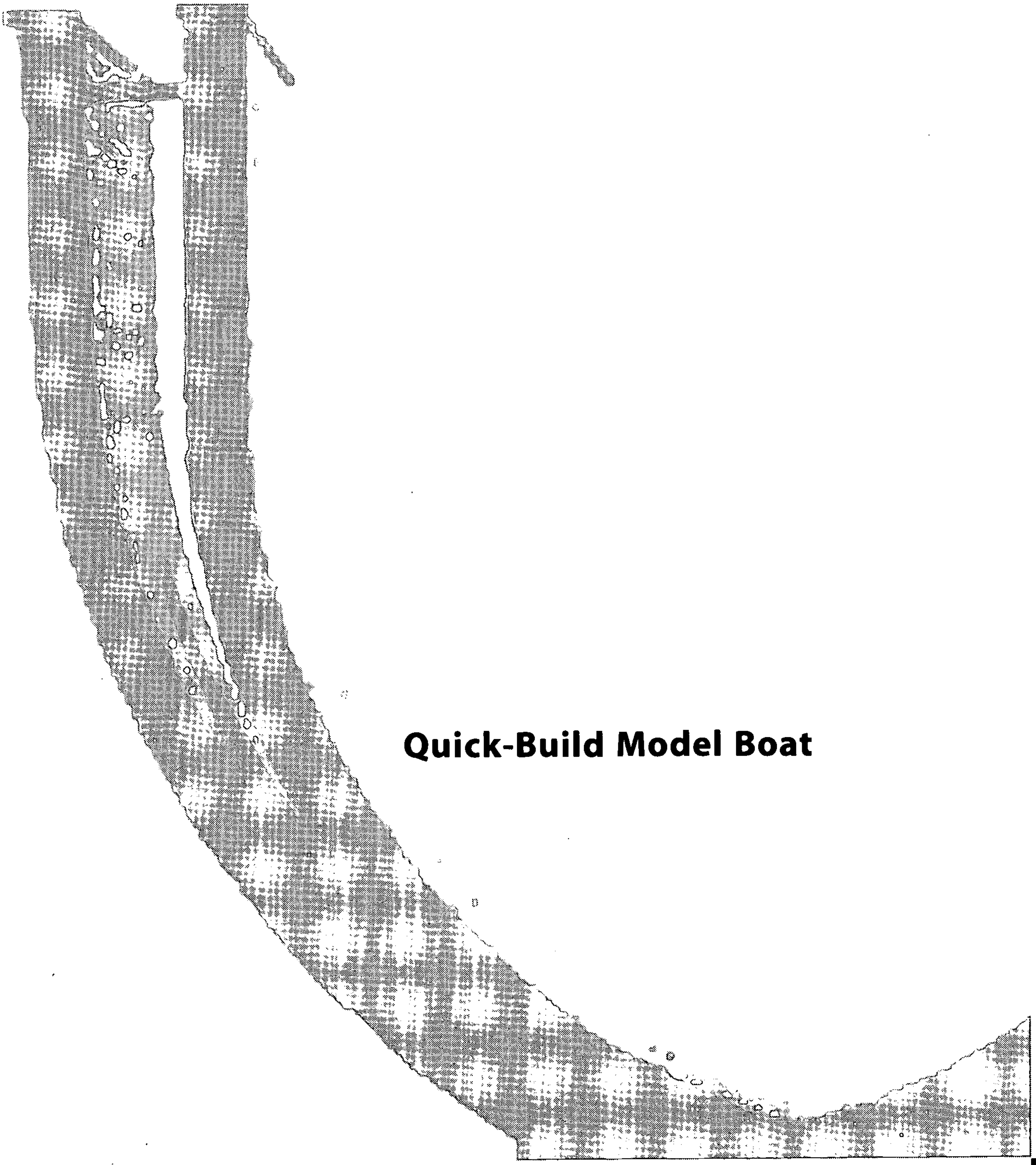
An inventory of students' prior knowledge is an important teaching and learning tool. Not only does the inventory help guide students toward the concepts they need to learn the most, but it also prepares them to accept new information in a manner that ties meaningfully to what they already know. At the end of *Construct-a-Boat*, students will be able to compare answers given at the beginning of the unit to those they will answer at the end of the unit.

Allow about 20 minutes for students to complete the *Snapshot*, then collect and retain.

MISCELLANEOUS SUGGESTIONS

This unit can be conducted with little or no computer use, or it can involve some or all aspects of computer modeling, data collection, design, and manufacturing. If you decide to use computer modeling, you will need to introduce these concepts briefly and indicate what level of expertise you expect students to acquire in these areas.

Activity 2



Quick-Build Model Boat

QUICK-BUILD MODEL BOAT

DAY 1

MATERIALS

- *polystyrene (hull)*
- *9-volt battery*
- *#22 AWG wire*
- *fan*
- *battery connector*
- *binder clip*
- *hot-glue*
- *large paper clips*
- *electrical tape*
- *switch*

TOOLS

- *saw*
- *pliers*
- *wire strippers*
- *wire cutter*
- *sandpaper*
- *hot-glue gun*

The Quick-Build is a simple model boat that you build to begin exploring the variables that affect boat performance. Your team can build it quickly, within one class period. Use the specified materials to build this model, and follow the technical instructions. You will then use the Quick-Build to make some baseline measurements. *Do not make any design changes before you make baseline measurements!* Here is why:

Building According to Specifications

It is important that you build according to the technical instructions and drawings provided. The Quick-Build ensures that every team starts in the same way, and you will be assessed on the *improvements* you will make to the Quick-Build's baseline performance. You must make the baseline measurements before you redesign anything so that you can measure improvements accurately. Be sure to check with your teacher before you make any substitutions for materials.

In this section, you are provided with:

- Materials and tools lists
- Technical instructions
- Technical drawings

QUICK-BUILD SPECIFICATIONS

Technical Instructions

1. Cut the polystyrene to meet requirements for length and width of the scale model hull according to the "Model Boat Quick-Build" blueprint.

2. Position the fan 2 cm from the Quick-Build stern. See the "Model Boat Quick-Build" blueprint for details.

3. Build the switch according to the "Electric Switch Detail Drawing."

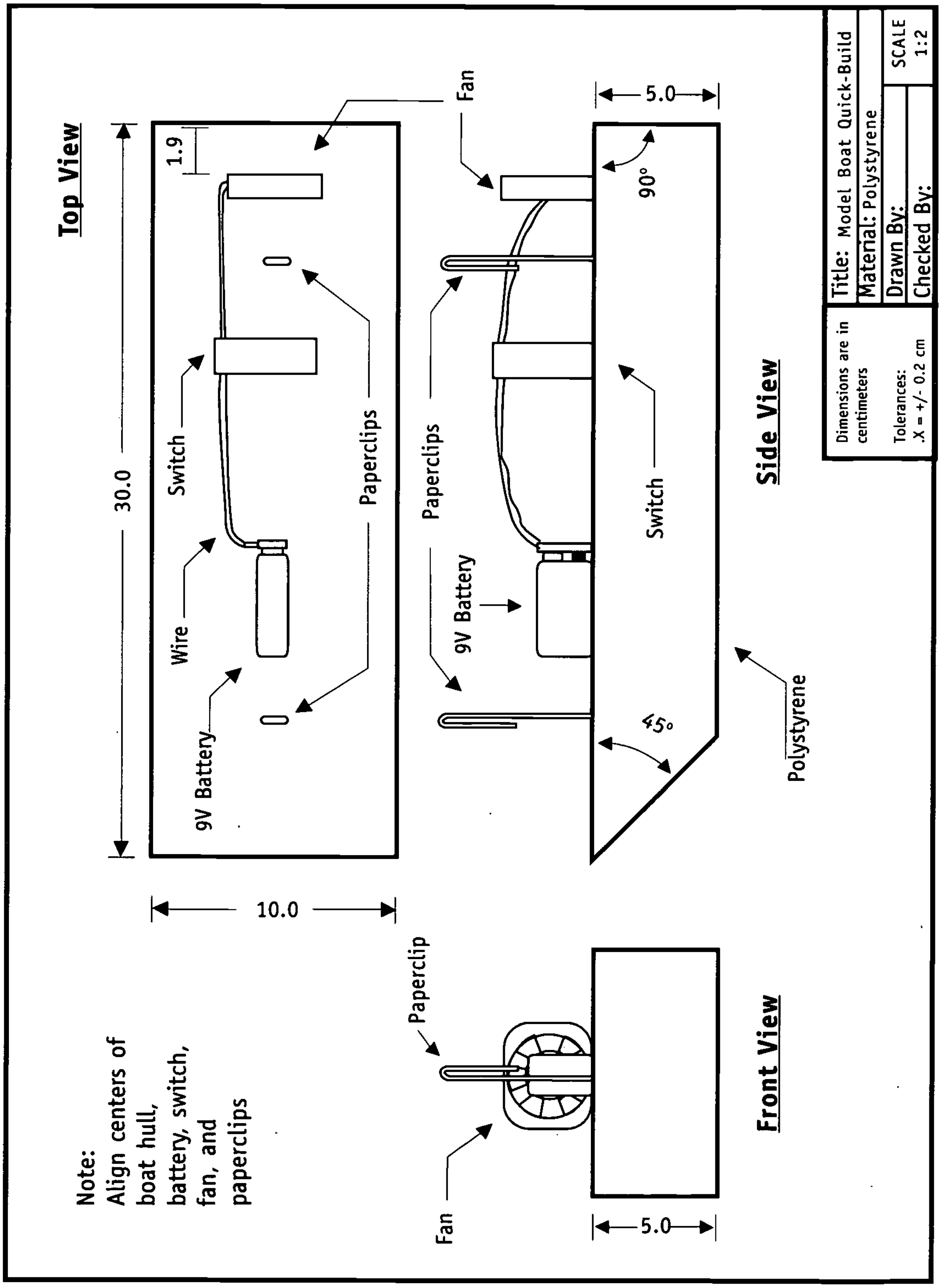
4. Build the electric system according to the "Electrical Drawings."

5. Place the 9-volt battery and switch on the top surface of the hull. The waterline is where the surface of the water meets the hull. Position the battery and switch so that the waterline is parallel to the deck. Fasten them in place using glue or tape.

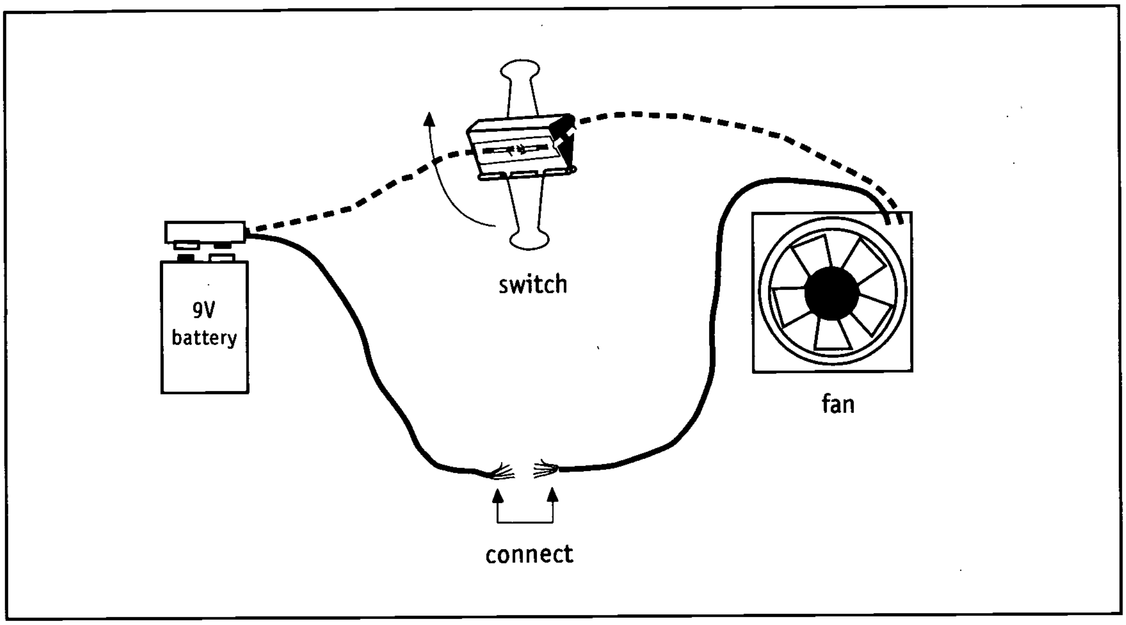
6. Straighten the two outer bends of each of two paper clips, and insert the straight end into center of the hull. The paper clip will look like an upside-down "J." See the "Model Boat Quick-Build" drawing for details.

7. All lengths must be accurate within two millimeters. This type of acceptable error margin is called *tolerance.*

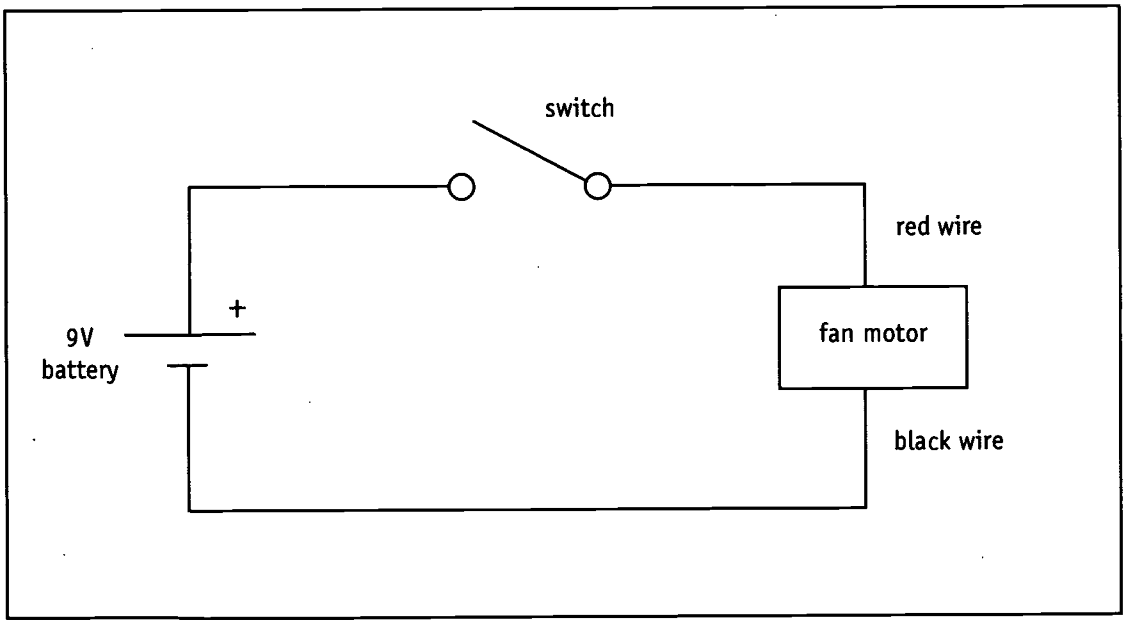
BLUEPRINT


Top View
30.0
10.0
1.9
Fan
Switch
Wire
9V Battery
Paperclips
Side View
5.0
90°
45°
Paperclips
Switch
9V Battery
Polystyrene
Front View
Paperclip
Fan
5.0
Note:
Align centers of boat hull, battery, switch, fan, and paperclips
Title: Model Boat Quick-Build
Material: Polystyrene
Drawn By:
Checked By:
SCALE 1:2
Dimensions are in centimeters
Tolerances: .X = +/- 0.2 cm

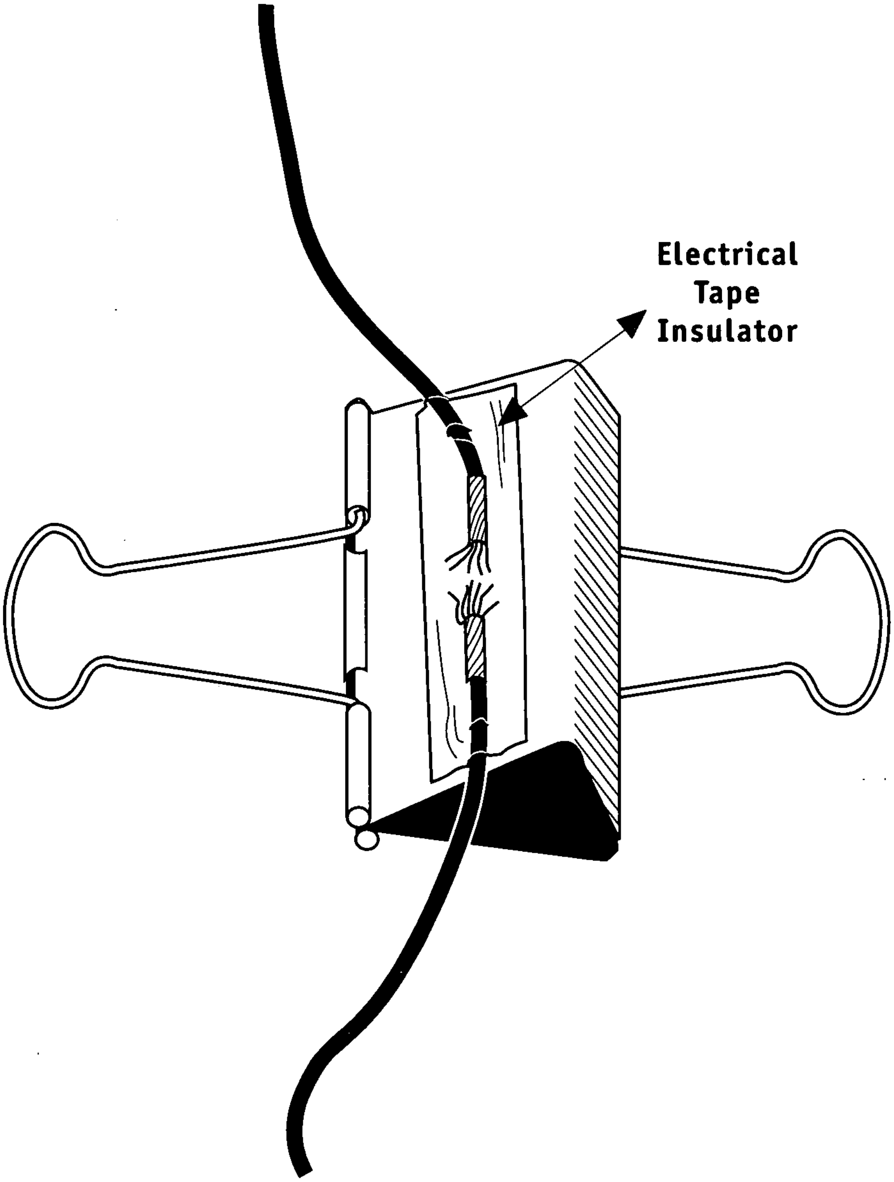
ELECTRICAL DRAWINGS



These drawings illustrate two different ways to show how the parts are connected.



ELECTRICAL SWITCH DETAIL DRAWING



MAKING THE TEST TANK

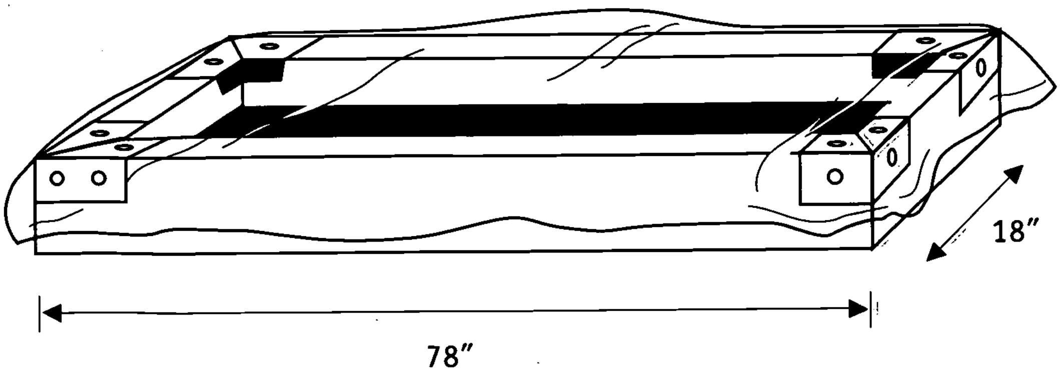
Materials List

Part	Type	Quantity
Sides	wood 2.5 m x 5 cm x 10 cm	2
Seal	6 mm plastic sheet	1 roll 60 cm wide
Corner Bracket	corner	30 cm
Nails	8 d	32
Duct Tape		1 roll
Guidepost		2
Guidewire	monofilament fishing line	1 roll

Technical Instructions

1. Fasten guideposts so that they are centered at each end of the tank.

2. Tie the monofilament fishing line to each guidepost, making sure that the height is adjusted so that the line can run through the approximate center of the paper clips on the Quick-Builds. Your ability to do this will be affected by the height of the water.



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EXPLORING THE MODEL BOAT SYSTEM

The Boat is a System

A system is a collection of interacting elements that function together as a unit. By studying the design of a boat as a *system*, you begin to understand the reasons why a boat performs well or poorly. Then you can improve the boat's performance by redesigning the most important elements of the system.

Exploring the Model Boat System

The purpose of this activity is to explore the performance of your Quick-Build before you make any design changes. As you explore, keep track of your observations and hypotheses about what affects the speed of the boat.

Observe

Run your Quick-Build along the water tank, and observe what happens to the boat, the guidance system, the water, etc. You don't have to take any measurements, just make qualitative observations. Describe what you see and try to explain your observations in the space below.

Make an "educated guess"

Discuss with other members of your team which elements in the model boat system will affect its performance the most. Write down what you and your teammates think. Here are some questions to help you get started:

- What makes the boat move? Is it the battery, the fan, the switch, the fishing line, or some combination of these elements?

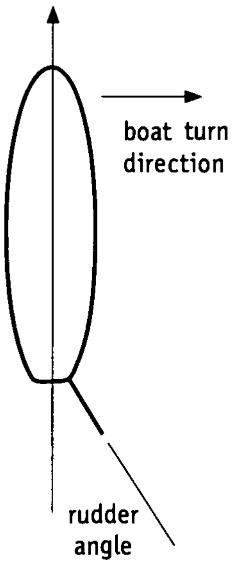
- What makes it hard for the boat to pick up speed?

- You are challenged to redesign the boat hull. What part does the boat hull play in helping with the boat's performance? How does it affect the other elements?

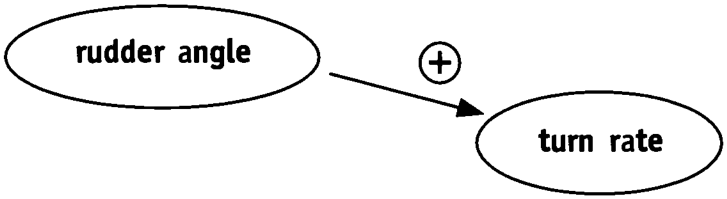
- Do you or your team have other ideas?

SYSTEMS MODELING INTRODUCTION

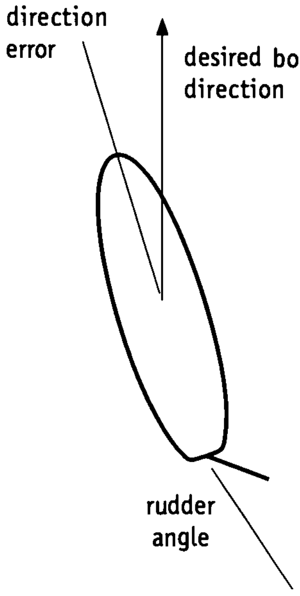
A system is a collection of interacting elements that function together. Below are examples of how to think about the boat *steering control system*.

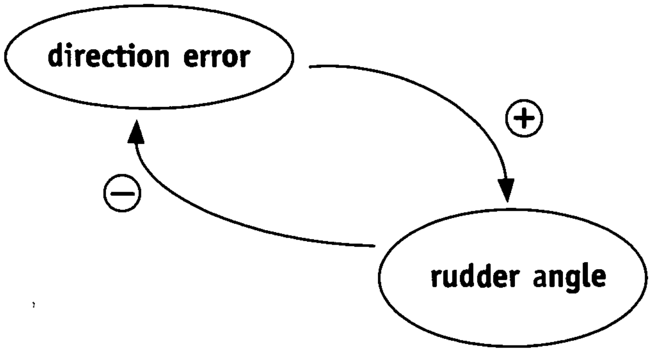


Example 1. The effect of the rudder on the boat direction. As the pilot increases the rudder angle, the turn rate increases. The *plus sign* means that an increase in rudder angle causes an increase in turn rate.



Example 2. The steering system of the boat, including the pilot. The boat pilot sees the error in the boat's direction and corrects by increasing the rudder angle. The minus sign means that an increase in rudder angle causes a decrease in the direction error. This is called "negative-feedback" and results in a stable system—the boat stays oriented in the desired direction.





CAUSAL RELATIONSHIPS

Linking Variables

Evaluate the following statement, then answer the questions below:
An increase in speed causes an increase in water friction.

SCILINKS®
THE WORLD'S A CLICK AWAY

Topic: friction
Go to: www.scilinks.org
Code: CAB03

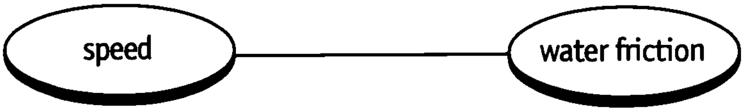
1. Is this statement correct?

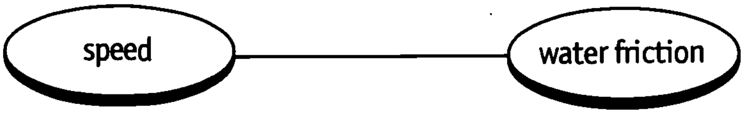
2. Why or why not?

3. **Definition**

   When a change in one quantity causes a change in another quantity *in the same direction*, we say that the first quantity has a *positive effect* on the second quantity. When a change in one quantity causes a change in another quantity *in the opposite direction*, we say that the first quantity has a *negative effect* on the second quantity.

   In the diagrams below, show two distinctly different ways to complete the link, each containing (1) an arrow head and (2) a positive or negative sign.





4. Combine the two links from step three to make one diagram.

5. State in words what your diagram shows.

OVERVIEW—QUICK BUILD

Making the Quick-Build

Student teams make the Quick-Build according to technical instructions and drawings provided in the unit. Teams are challenged to exercise the communication skills of translating technical texts and drawings into a real object.

Exploring Model Boat Performance

Teams explore the qualitative performance of the *Construct-a-Boat* Quick-Build before making any design changes.

Systems Modeling Introduction (Homework)

Students are introduced to the use of systems diagrams to represent causal relationships.

Causal Relationships

Students are introduced to diagrams for linking functionally related variables. They explore the relation of speed to friction as it will impact their boat's performance.

TEACHING SUGGESTIONS

The Quick-Build class needs to be fast-paced.

Due to the variation in fan motors and other elements of this lab, it is particularly important that you preview all aspects of the Quick-Build assembly before working with students. You should modify instructions to fit your circumstances. You should also feel certain that all teams will be able to complete the Quick-Build tasks within the class time assigned to each task.

Students will want to test their boats immediately, but you should delay performance measurements until the research section of this unit, where a framework for performance testing is developed. During the Quick-Build, emphasize frame questions to elicit qualitative answers such as "more" or "less." Questions requiring numerical answers should be postponed until later in the unit.

Tolerances and assembly drawings are included to provide a realistic, machine-shop setting. If technology education is a high priority in your classroom, you will want to enforce strict adherence to this aspect of the unit. Otherwise you can decide which aspects best suit your objectives.

DAY 1

MATERIALS

FOR EACH STUDENT
Student Activity Sheets
- Quick Build Specifications
- Making a Test Tank
- Exploring the Model Boat System
- Systems Modeling

FOR EACH TEAM
Building Materials
- *polystyrene (hull)*
- *9-volt battery*
- *#22 AWG wire*
- *fan*
- *battery connector*
- *binder clip*
- *hot-glue*
- *large paperclips*
- *electrical tape*

Tools
- *saw*
- *pliers*
- *wire strippers*
- *wire cutter*
- *sandpaper*
- *hot-glue gun*
- *metric ruler*

PREPARATION

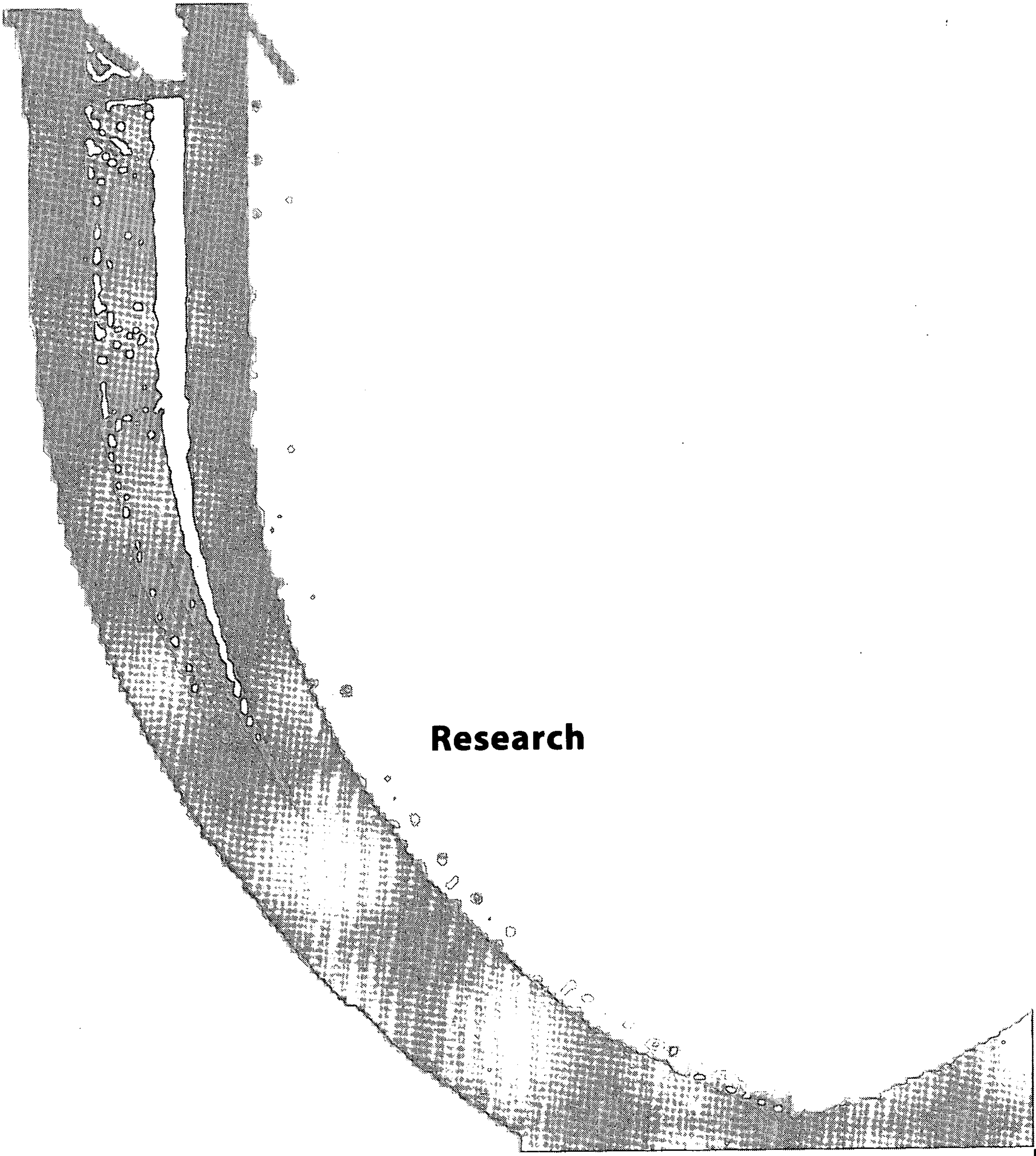
- *Obtain Quick-Build construction and testing materials.*
- *Run through Quick-Build assembly yourself.*
- *Modify instructions to fit your materials.*
- *Preview library and Internet resources.*
- *Consider noise, safety, access to water (and AC power—optional) in choice of worksite.*
- *Organize materials for orderly access.*
- *Determine strategy for student team formation.*
- *Prepare test tank.*
- *Contact local boat builders (optional).*

MISCELLANEOUS SUGGESTIONS

The Quick-Build and subsequent research sections stress systematic descriptions of qualitative relations. It is likely that these considerations will be new to your students.

Do not be surprised if your students show disdain for the qualitative questions in these materials. Your students may also feel intimidated by the apparently simple, but in reality very difficult, reasoning that lies behind the qualitative questions. It is very important that you show your own enthusiasm for these questions and that you insist that students know how to handle them before moving on to quantitative calculations.

Research on the learning of mathematics and science has shown that standard modes of instruction place far too little emphasis on these essential aspects of mathematical thinking (Stigler and Hiebert 1999). Comparisons of expert and novice problem-solving practices show that a key characteristic of expert problem-solvers is that they spend a great deal of time with qualitative issues before ever considering a numerical calculation. Novices tend to employ a formula immediately, often without any understanding of its function or suitability.



Research

3 DAYS

OVERVIEW—RESEARCH

You have completed the Quick-Build and made rough observations of the *Construct-a-Boat* system. Your team's challenge is to improve the performance of your boat, so that it will achieve a higher top speed as quickly as possible after starting. You will first need to establish some baseline measurements, then collect data on variables that are important to high performance, and investigate how these variables work with or against each other.

There are different ways to go about meeting your challenge. Trial-and-error is one method—fiddling around until something works. Trial-and-error is usually more effective when it is not an entirely random process; an educated "try" by an investigator who is alert to outcomes can yield shortcuts. However, time investment, cost effectiveness of materials, and labor are usually important considerations that work against the benefits of trial-and-error.

A systematic approach to research involves careful planning and documentation, and has several important strengths. Planning allows for division of labor, a sensible cost estimate, and a manageable time schedule. Estimates and schedules are essential if you want to finish the project on time and at a price you can afford.

Scope of Work

- Experiment with your Quick-Build to determine baseline data.
- Research the science concepts related to the performance of the boat.
    - Identifying variables and effects
    - Scaling
    - Minimizing surface area
- Read science text books to study the relationships among force, speed, and acceleration.
- Explore the use of conceptual models, computer modeling, and scale models in explaining, designing, and evaluating a physical system.

BASELINE MEASUREMENTS

Purpose

To show that you have met the challenge scientifically, you will need to compare your Quick-Build performance data to your final design. You can use the Quick-Build performance data as a baseline, and from that data, you can tell if your design changes actually improve performance. Remember that your challenge is to redesign and build a boat hull that will:

(1) achieve the highest top speed
(2) achieve the greatest acceleration

Collecting Performance Data

In the space below, write down a plan for collecting data to show

(1) the top speed of a model boat
(2) the time it takes for the boat to achieve top speed

In your plan, describe what you are measuring, how you are measuring it, what calculations you need to make, how many people are needed to take measurements, and other pertinent information.

PROCESS ALERT!

You will probably revisit these research activities several times, because as you move on through the development activities, you will find that you need information you had not previously identified! No matter how carefully you plan, you may make mistakes; be alert to learn from them and adjust your plans.

Topic: presenting data
Go to: www.scilinks.org
Code: CAB04

ORGANIZING THE DATA

Well-organized data will help you keep track of improvements in your designs and will help you make better designs in later stages. Carefully collect and record your data. Include notes on unexpected occurrences, such as someone bumping the water table. Organize your data so that you can make sense of it and use it later when you are redesigning your boat hull.

Set up Tables for Recording Original and Calculated Data

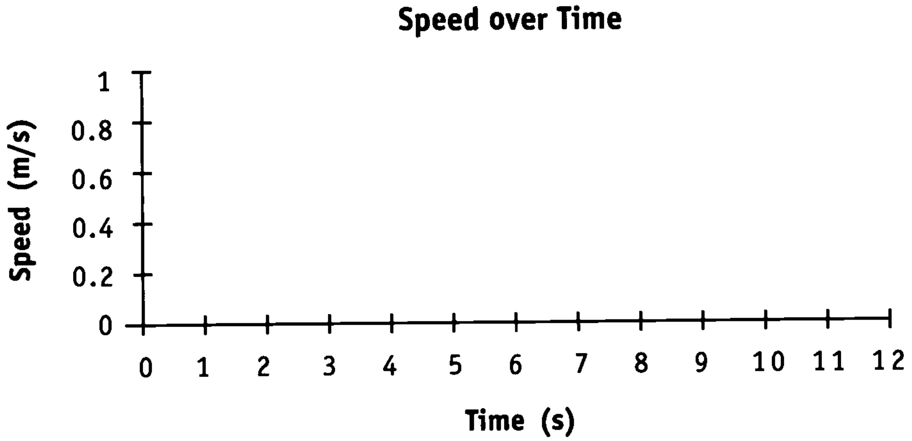
Here is an example of recording and calculating data for the change of speed over time.

Time on stopwatch (in seconds)	Distance from starting point (in meters)	Speed @ distance (in m/s)	Speed change = speed$_n$ - speed$_{n-1}$ (in m/s)

In your notebook or laboratory journal, set up tables for all variables that you have identified, measured, or calculated. Your tables should not look exactly like the one above, which is given only as a rough example. Below your table, leave space for notes on unexpected occurrences.

Represent Your Data Using Graphs

Think about what you might want to study or show graphically. Graphs allow you to visualize relationships between the variables you are measuring and to see changes in your data. There are different kinds of variations over time: distance traveled, instantaneous speed, and acceleration all change over time. Here is an example of how you may represent this kind of variation:



Make similar graphs for all variables that you have identified, measured, or calculated.

Are There Other Ways to Work with Data?

If you have access to a computer and spreadsheet software, such as Excel or ClarisWorks, try making the tables and graphs using a spreadsheet.

IDENTIFYING VARIABLES

You have already made measurements of the speed of your Quick-Build, and have probably noticed that the measurements vary over time. You will now identify the factors that could produce these variations.

Improved performance for the *Construct-a-Boat* challenge was defined as achieving higher top speed *and* reaching top speed in a shorter time. The *scientific* way to meet this challenge is to determine which variables affect improved performance. Once you've identified these variables, you can make sure to include these variables in your design changes.

Discuss variables with members in your work group, then complete the table below.

Variable	Why is it important?	How do you measure it?
mass		
force of the motor		
friction of the water		
wet surface area		
surface roughness		
[add your own]		

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Plan for Collecting Data for Model Boat Variables

Complete the table on the next page for a plan to do your experiments. Make sure that your plan provides answers to these questions about *each variable* that you have identified:

1. Is this variable directly measurable? If not, what can you measure to obtain quantitative data on this variable?
2. How do you do the measurement? Specify tools and comment on your expectation for accuracy.
3. Will you need to do any calculations from your measurements?
4. How do you calculate for the variable that you want to study? What assumptions or estimates do you need to make?

Use the space below to put down ideas, either your own or those of your teammates. These ideas do not have to be perfect or complete, and you do not have to write in complete sentences. Phrases, charts, or diagrams can sometimes do a better job, as long as you can come back to them later when you need to revisit your first thoughts.

SCILINKS®
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Topic: mass
Go to: www.scilinks.org
Code: CAB05

Topic: force
Go to: www.scilinks.org
Code: CAB06

Measurement Plan

Variable	What to Measure	How to Measure	Calculations
mass	*weight*	*Put model on triple-beam balance*	*mass = weight/ (acceleration due to gravity)*
force of motor			
friction of water			
wet surface area			
surface roughness			

WORKING WITH THE VARIABLES

We want to know how each variable affects:

(1) the top speed of the boat, and

(2) the time it takes the boat to reach top speed.

Design a table (or some other way to record your data) so that you can work with the variables you have planned to investigate. Use the space on this page to put down your ideas, and keep legible copies of your measurements for later reference.

SCALE MODEL PREPARATION HOMEWORK

The shape of the scale model is the same as the actual boat you hope to design even though the model is smaller. You can calculate the linear scale factor by taking the ratio of the actual boat length to the model boat length. This will be useful to determine other dimensions of the model boat. Calculate what the linear scale factor would be for a 30 cm-long model of a 70 meter boat and write it below.

Linear Scale Factor =__________

Use the boat design specifications and the linear scale factor to determine how wide the 30 cm model boat should be. The width of a boat is called the *beam*. For your ferry, the beam is 18 meters.

Real Boat Length = ____________

Model Boat Length = ____________

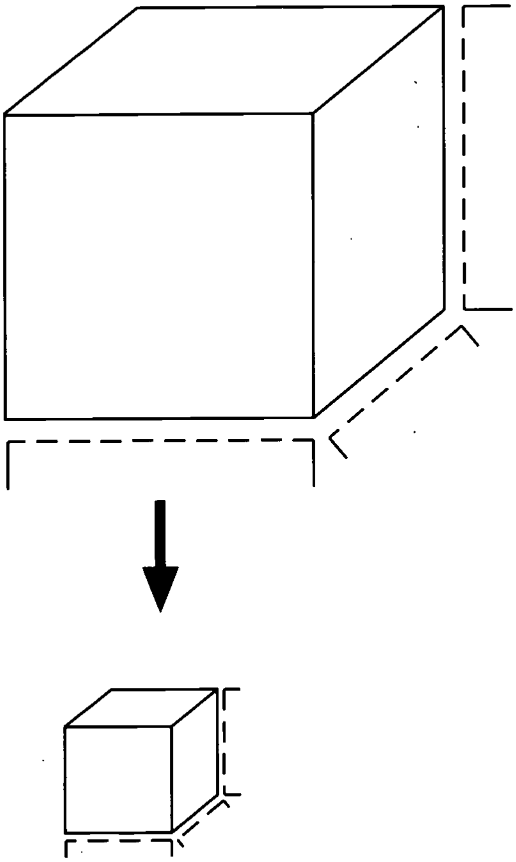
Real Boat Beam = ____________

Model Boat Beam = ____________

APPLICATIONS OF SCALING

Try using the linear scale factor to calculate the weight of the model boat. Explain why you cannot use the result. Use the space below to show your work and explanation.

Work out a strategy to estimate the weight scale factor for the model boat; it should allow you to calculate the weight in *grams*. Write the strategy below and include any assumptions you must make.



Weight Scale Factor = ______________

SCILINKS®
THE WORLD'S A CLICK AWAY

Topic: buoyancy
Go to: www.scilinks.org
Code: CAB07

SCALE MODEL EXTENSIONS HOMEWORK

1. Use the Weight Scale Factor to calculate the weight for the model boat based on the Design Brief data for a real boat with no cars or people. Write your solution below in grams.

Model Boat Weight = __________

2. Estimate the maximum weight of people and cars that the ferry M/V Nantucket carries.

People and Cars Weight = __________

Determine the scale weight for people and cars in *grams*.

People and Cars Scale Weight = __________

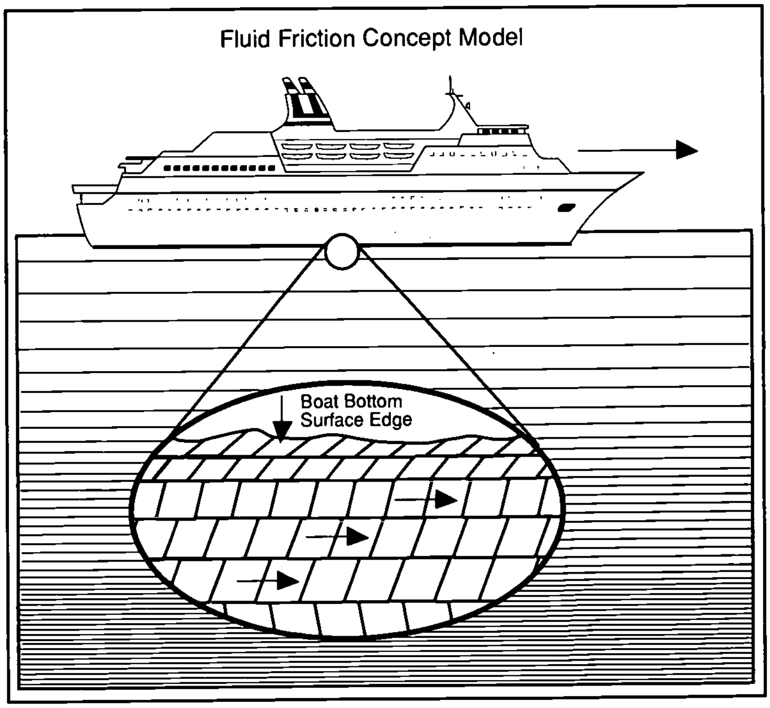
FLUID FRICTION DYNAMICS

Boat designers and builders use the following mathematical model to determine efficient hull designs. The most efficient hulls are designed to have the least friction. The model is a formula:

$$\text{Friction Force} = \underset{\substack{\uparrow \\ \text{Friction} \\ \text{Coefficient}}}{C} \times \underset{\substack{\uparrow \\ \text{Wet Surface} \\ \text{Area}}}{A} \times \underset{\substack{\uparrow \\ \text{Speed}}}{V}^{2}$$

The *wet surface area* is the part of the boat hull that is in contact with the water. The *friction coefficient* is determined by the roughness of the wet surface area. The designer tries to create a more efficient hull by reducing the wet surface area. Builders can create more efficient hulls by reducing the friction coefficient. The trade-off for the builder is to balance the need for a low coefficient of friction with a durable, affordable, hull surface.

Fluid Friction. In this model, the ship slides through the water and pulls layers of water along with it. An enlarged view shows that layers closest to the boat hull are pulled the fastest. The roughness of the hull surface determines how much water is pulled along with the boat. This roughness is represented by the friction coefficient.



MINIMIZING SURFACE AREA

The Question of Surface Area vs. Volume

Fluid friction force, which reduces the speed of the boat, is dependent on the friction coefficient and the wet surface area of the boat hull. One problem that a designer must solve is how to minimize that wet surface area. Given a specific volume, how would you choose a shape that will give you the smallest wet surface area of the boat hull?

What You Need

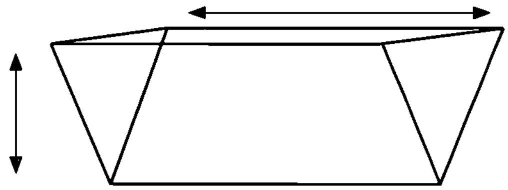
- measuring cylinder (1 liter)
- cardboard three or more sheets 30 cm x 30 cm or longer
- fine, dry sand
- spring balance
- glue
- markers

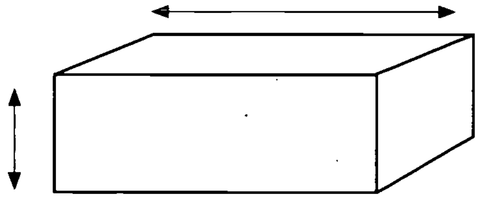
Build a Boat

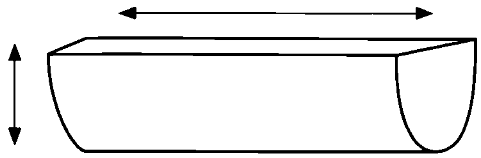
Using cardboard, build three rectangular open containers, with the sides and bottom to form the shape of a square, a triangle, and a semicircle.

The top rectangular opening for all three boxes must be of identical measurements. The height must also be the same for all three containers.

Record your measurements on the diagrams provided here.

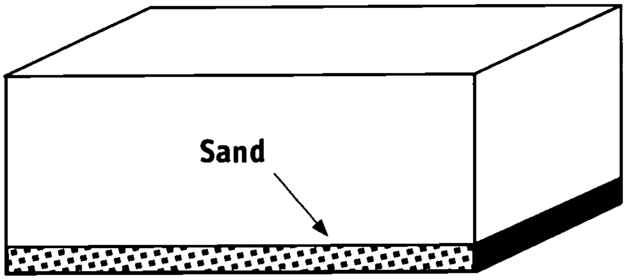






Fill with Sand

1. Into each of the three containers, pour a carefully measured volume of 1000 cc (1 liter) of sand. Gently shake each one so that the sand is level when the container is standing flat on the table top. Mark the fill-line all the way around on the inside surface of the container.



2. Discard the sand from each container and unfold each along the seams.

3. Compute the total area of the inside surface that touched the sand. Note the units you use for area.

4. What is your conclusion about the relationship between volume and surface area?

5. How will this information help you in the design of the boat hull?

MATERIALS

FOR EACH STUDENT

Student Activity Sheets

- Overview—Research
- Baseline Measurements
- Identifying Variables
- Scale Model Preparation
- Applications of Scaling
- Scale Model Extensions
- Fluid Friction Dynamics
- Minimizing Surface Area

FOR EACH TEAM

- *Quick-Build boat*
- *stop watch and meter stick*
- *graph paper*
- *set of 27 identical solid cubes and spheres of different diameters but of identical material*
- *one liter of fine sand*

FOR CLASS

- *accurate balance*
- *water tank*
- *computer-based or graphing calculator-linked position detector (optional)*
- *set of measuring cups (optional)*

PREPARATION

- *Review preparation issues for Quick-Build.*
- *Prepare support materials for discussion of scaling.*
- *Define Laboratory Journal requirements.*

3 DAYS

OVERVIEW—RESEARCH

Student teams work through a tightly structured series of activity sheets to familiarize themselves with the skills and structures they will need in the more open-ended Development sections.

Baseline Measurements

Students make speed vs. time measurements of their Quick-Build model so that they may determine performance improvements through their design changes.

Identifying Variables

Teams list important variables and plan how to measure each.

Scale Model Preparation Homework

Students are introduced to scale modeling as an accurate three-dimensional (3D) representation of the actual object, and determine some physical specifications for the model boat by scaling down from the real boat specifications in the design brief.

Applications of Scaling

Students figure out why the linear scale factor does not work for weight (weight scales as volume, not length) and then determine a weight scale factor. They may use formulas from mathematics (length^3) or empirically determine the scaling factor by cutting and weighing cubes of different sizes.

Scale Model Extensions Homework

Students use the weight scale factor to determine the model boat weight when empty and when loaded with people and cars.

Fluid Friction Dynamics

Students are introduced to the quantitative relationship linking speed and friction for a boat hull.

Minimizing Surface Area

Using a constant volume of sand poured into 3D shapes (open trays of circular, triangular, and rectangular cross-sections), students explore the relationships between area and volume. This provides some baseline experience for designing a boat hull with minimum wet surface.

This activity should be revisited after students encounter The Designer Problem *development activity. The initial introduction should be brief.*

TEACHING SUGGESTIONS

This activity will take three class sessions. The research portion of the *Construct-a-Boat* unit is tightly structured due to the relative complexity of the tasks required of the students and the need to ensure that all students acquire the skills necessary to advance to the Development stage. If time permits, you may want to add library and Internet search activities to this activity. A visit to a boat builder would also be an excellent extension option.

Devote the first class to the *Overview, Baseline Measurements,* and *Identifying Variables* sections. Most of the class will be conducted with teams working independently, but during final wrap-up, teams should share their ideas about variables to be measured and techniques of measurement. Each student should keep notes in a Lab Journal on both team and full class activity.

The next class should be used for the exercise in applications of scaling, because this exercise may prove more complicated than it looks. For students who understand linear, quadratic, and cubic scaling, the exercise is simple (and will not require more than a few minutes). For students who do not understand scaling, this will be a difficult and highly important lesson.

The third class period is devoted to fluid friction dynamics and to minimizing surface area. Most of this class will be taken up with experimentally investigating the relation of shape to surface area. An understanding of scaling is essential background for these measurements. If your students do not yet grasp scaling, you might delay this class until the middle of the Development activity.

DAY 1

Encourage students to develop their own methods and ideas through the *Baseline Measurements* and *Identifying Variables* activity sheets. You will need to observe their activities carefully. It is quite possible for students to design methods for measuring speed that do not work well in practice. Try to have the teams discover these errors themselves, perhaps by responding to your probing questions. If one team has developed a good system, ask that team to work with a team that is still struggling. Avoid giving all teams a set procedure, because students will be able to implement a procedure without really understanding what they are doing.

If you have access to a computer or graphic calculator-linked position and velocity detector, you will want to set this up on the test tank. It may be necessary to add a large target sail-like structure on the boat in order to get good position data. You will need to pretest this setup and may have to modify Quick-Build instructions to ensure good data recording.

Use a brief, full-class discussion to make sure that all teams have a complete list of important variables. Students may wish to investigate variables that you feel are unimportant or are a diversion from the main focus of the unit. Try to find a suitable balance between cutting off their curiosity and allowing the class to be diverted to a completely different topic.

DAY 2

If your class has difficulty with the material on scaling, use the optional second sheet on weight scaling. Provide each team of students with 27 identical cubes, which they can stack to create a large cube three units long on each edge. Also provide objects in a range of sizes and of uniform density. Have the students predict the weight of one size based only on the weight of a different size and a length measure from each. Allow students to repeat this prediction and measurement several times before attempting to explain why weight will be proportional to the cube of the linear measure.

Cubes and spheres are the best shapes for this exercise. Other shapes may introduce confusion concerning the best linear measure. If students have developed a fairly strong grasp of the concept, you may want to refine it by introducing cylinders of the same length but of different diameters. Here the weight scaling will depend on the square of the diameter (not the cube). It is also useful for students to see that cylinders of the same diameter but of different lengths will have weights that scale linearly.

Encourage students to explain these phenomena to each other and be very patient with any difficulties students may have in understanding your explanations. Scaling is a *very difficult* concept to learn even though it is a simple and obvious concept to remember *once it is understood.*

One powerful way to stress the nature of cubic scaling is with two large cubes, the smaller being light enough to lift with some effort and the larger being impossible to budge.

DAY 3

The student activity sheet, *Minimizing Surface Area*, assumes an understanding of the principle that a boat must displace a volume of water equal to its weight. Most students know of the Archimedes Principle, but many might not really understand it. If this is the case, you could remind the students of the story of Archimedes in the bathtub.

To understand boats, it is important to distinguish floating objects from objects that are completely submerged. You might need to provide some time for informal investigation of these questions.

On the *Minimizing Surface Area* activity sheet, the volume of sand represents the volume of water that must be displaced by the vessel. The top of the sand represents where the water line would be. Unfolding the container reveals the surface area that would lie below the water line. Different shapes will yield different surface areas.

Some students might be troubled by the results of this investigation. The minimum surface area would be generated by a spherical shaped boat, yet no surface boats are designed as spheres.

We have been ignoring the effect of the frontal cross section. The need to design for a small frontal cross section is what forces designers to choose long thin designs of greater length than beam. The *Minimizing Surface Area* activity is useful in choosing between different possible cross sections. But minimizing surface area is not the only important consideration. The stability of the boat depends very much on the shape of the cross section and a good design must consider the trade-off between stability and minimal wet area.

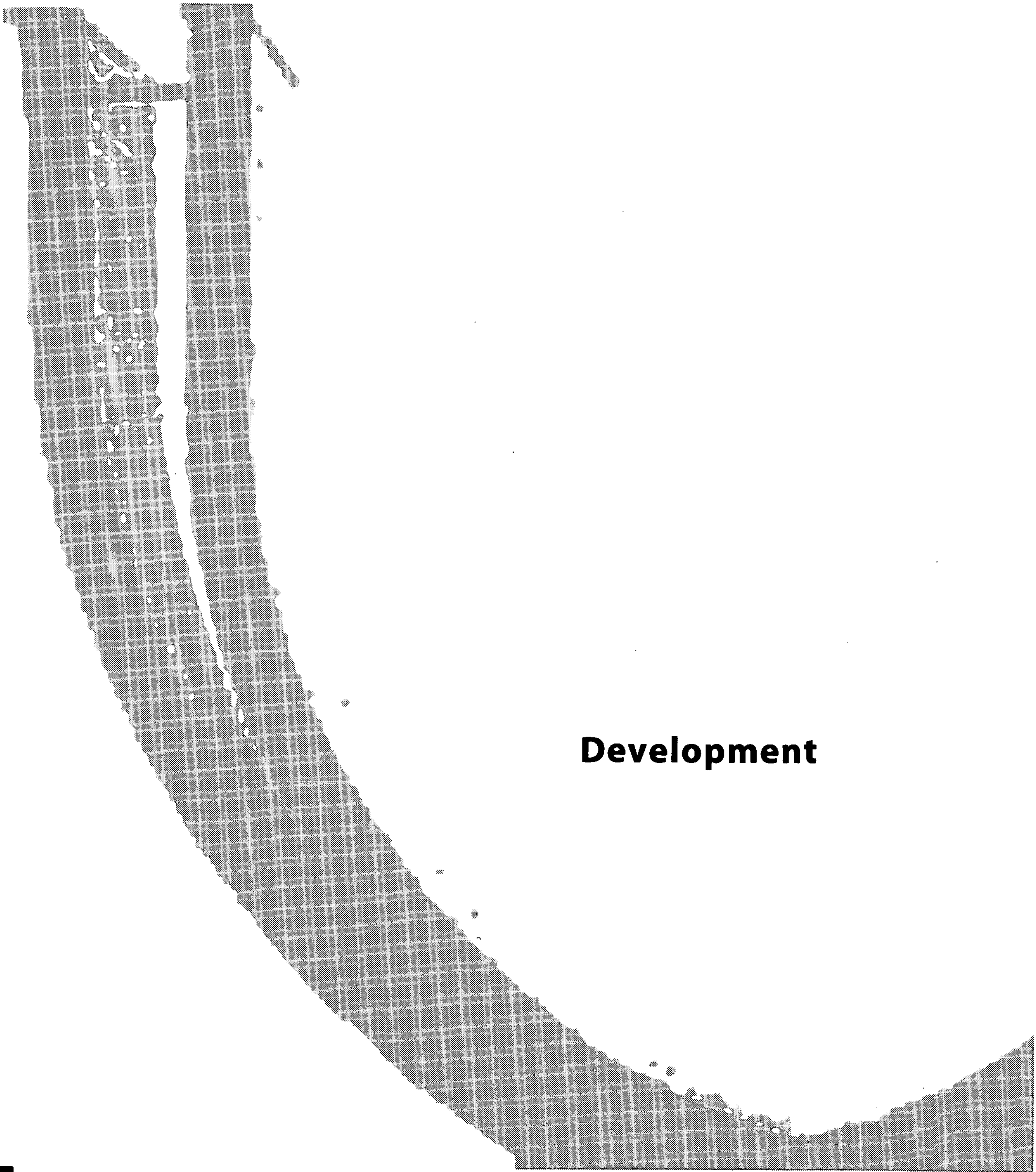
Note

The mass vs. weight issue is a tricky one, requiring teachers to give special attention to the actual measurement procedure and to students' misconceptions.

Weight is the force due to gravity, and is typically measured with a spring scale. Mass is the "amount of stuff" and is generally determined by comparing the sample to another standard sample. A triple beam balance is typically used to determine mass.

Confusion can arise if someone "weighs" something on a spring scale (as in this activity) and gives its weight in, say, grams, a measure of mass.

The relationship, weight = mass x force of gravity, allows us to indirectly measure a weight by measuring its mass on a triple beam balance.



Development

OVERVIEW—DEVELOPMENT

4 DAYS

You have completed activities investigating a model boat system. You have also researched the relationships among force, speed, and acceleration. To meet the *Construct-a-Boat* design challenge, your team will now develop a prototype that allows your re-designed model boat to achieve the highest top speed possible after starting in the fastest time possible. In designing and building this prototype, keep in mind that different variables may affect different aspects of the boat performance, and that you may not want to sacrifice too much of one aspect for the sake of another.

Scope of Work

- Redesign your boat hull so that your newly re-designed model boat will have improved performance over that of the Quick-Build.
- Build your prototype and test its performance.
- Collect performance data for the re-designed model boat, for comparison with the Quick-Build.
- Evaluate your design modifications.

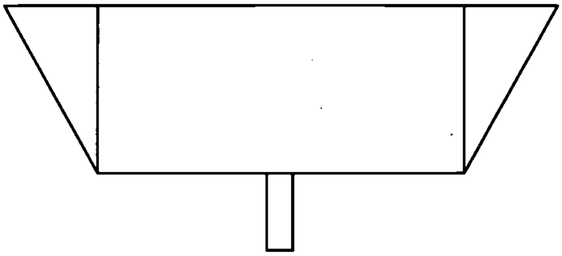
Good planning is essential to good design. Look again at your research where you identified variables and wrote down key factors that affected performance. Think how best to combine design options to improve performance. Be creative within your objectives and constraints. Review the *Inquiry Process* and *Design Process* resource sheets for ideas on next steps. Evaluate your prototype critically and make modifications until you are satisfied with improved performance, or are simply out of time. Remember to reflect on your process, because how you go about your design, and what you learn, are key elements in the Communication and Assessment activities to follow.

DESIGNER PROBLEM

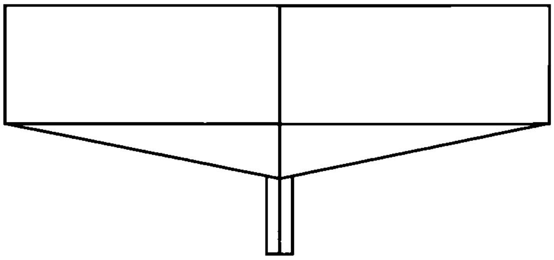
Invent a new design that improves the performance of the model boat hull and sketch your design. Propose a redesigned boat hull:

(1) Provide diagrams of the hull, including dimensions.
(2) Include explanations based on your research for how your design improves the model boat performance.

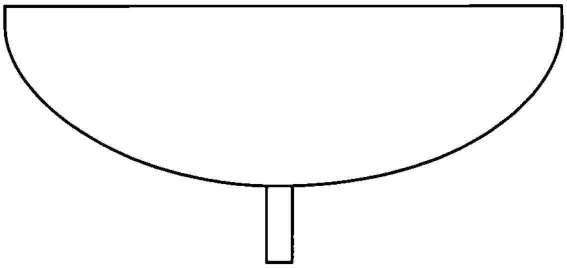
Here are some examples of hull shapes:



Flat Bottom



V Bottom



Round Bottom

BUILDER PROBLEM

Propose *two* distinct methods to minimize fluid friction and describe them in the space below. Use additional pages for sketches if that helps your explanation.

Design and conduct a test to determine improvements in the friction coefficient for the model boat. If you can, try using the computer model to understand better how the friction coefficient affects the model boat performance. Describe your test below.

PROTOTYPE CONSTRUCTION

Proposal

Revisit the *Design Brief* and propose a design of a model boat that would show improved performance—a higher top speed and a shorter time to reach top speed. In the space below, summarize the features of your new design and the rationale for including those features.

Materials

List materials required for the construction of your redesigned model boat:

Schematics

On separate pages, make technical drawings for the construction of your new design. Include a side view, front view, back view, and top view. Specify dimensions in metric measurement units on each of the drawings.

Construction

Build your model boat according to the specifications of your team's design. If you must make modifications as you are building, take note of the modifications in your laboratory journal.

EVALUATING YOUR NEW DESIGN

Purpose

Obtain performance data and compare these data to the baseline measurements, so you can tell whether your design changes actually improved performance.

Collecting Performance Data

Your challenge is to redesign and build a boat hull that will:

(1) achieve the highest top speed
(2) reach top speed as quickly as possible after starting

To show scientifically that you have met your challenge, you will need to compare performance data of the Quick-Build to those of your redesigned model. For the comparison to be valid, you need to collect data for your new model the same way that you did for your Quick-Build.

Collect data to show or calculate:

(1) top speed of model boat
(2) time it takes to achieve top speed

Set up tables for recording original and calculated data

You have collected, recorded, and represented data obtained from working with your Quick-Build. Now collect data for your newly designed model boat. It is important to take your measurements in the same way that you did when you worked with your Quick-Build. You should also represent the new data in such a way that you can make unambiguous comparisons of the performance data sets. Pay special attention to the units of measurement.

Represent your data using graphs

When you make graphs from your data, try to work with a scale that accommodates the performance data for both the Quick-Build and the new design. Overlay the two graphs if you can.

Make similar graphs for all variables that you have identified, measured, or calculated.

Comparing Performance Data

1. Did either or both of your Quick-Build and the newly re-designed model reach a maximum speed? ***Yes / No***

   top speed of Quick-Build =
   top speed of new model =

2. How long did it take each of your two models to reach its maximum speed?

   acceleration time for Quick-Build =
   acceleration time for new model =

3. Compare the performance of your new model to that of your Quick-Build. Provide a brief qualitative description below.

4. How would you describe the improvement in performance quantitatively? What calculations do you need to make?

5. Summarize your results and explain how you have achieved them.

4 DAYS

OVERVIEW—DEVELOPMENT

The object of the work in this section is for students to redesign their boat hull to obtain improved performance over that of the Quick-Build.

In the *Designer Problem* activity, students consider alternative shapes for their hulls that reduce the wet surface area. Next, in the *Builder Problem*, students develop procedures to test for improvements in frictional drag. The *Prototype Construction* activity is an opportunity to put it all together. Finally, *Evaluating Your New Design* lets students test their improved designs to compare boat performance to the baseline measurements made with the Quick-Build.

Time

This activity will take a minimum of four class sessions.

When possible, several days should be allotted to prototype construction, allowing students to undertake several redesign cycles.

TEACHING SUGGESTIONS

Designer Problem

The quality of the *Designer Problem* activity depends strongly on the fabrication techniques you are willing to explore. In the simplest case, where only straight cuts are permitted, all designs will be limited to flat, angled surfaces. Curved surfaces are possible if you allow sanding (although this is difficult with polystyrene). Polystyrene may be melted with a hot iron and molded into virtually any shape. However, this technique does release fumes and may create a small fire risk. Therefore, it is not recommended unless you have access to a shop with appropriate venting and safety features. Working with wood instead of polystyrene is also an option if you have access to appropriate tools and work space.

Be sure students understand whatever limits you have imposed on the fabrication strategies before they begin the *Designer Problem* activity.

Builder Problem

There are two variables to consider in the *Builder Problem* activity: surface area and surface finish. Because the previous activity dealt with surface area, students will be largely concerned

MATERIALS

FOR EACH STUDENT

Student Activity Sheets

- Overview—Development
- Designer Problem
- Builder Problem
- Prototype Construction
- Evaluating Your Design

FOR EACH TEAM

Materials

- *polystyrene (hull)*
- *9-volt battery*
- *#22 AWG wire*
- *fan*
- *battery connector*
- *binder clip*
- *hot-glue*
- *large paper clips*
- *electrical tape*

Tools

- *saw*
- *pliers*
- *wire strippers*
- *wire cutter*
- *sandpaper*
- *hot-glue gun*
- *electric iron (optional)*

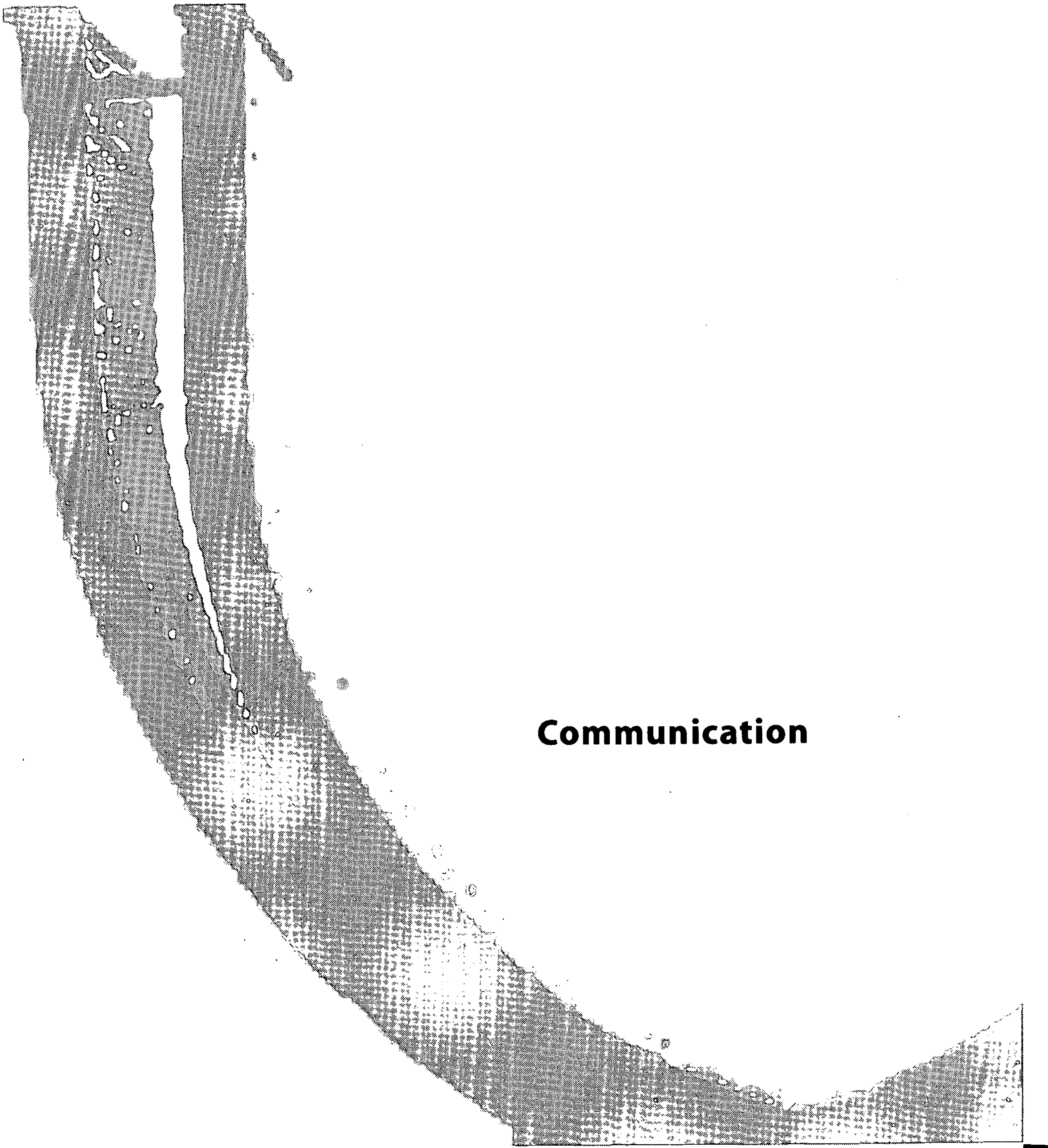
PREPARATION

- *Prepare tank test area.*
- *Arrange for team work areas.*
- *Prepare fire safety measures if polystyrene will be heat treated.*
- *Review Laboratory Journal requirements.*

with surface finish for this activity. Fabrication techniques are very important for determining the range of available options. The measurement of surface drag has been left for students to define. They may wish to measure surface smoothness by feel or by measuring the force needed to drag some object across it. Alternatively, they may choose to measure the drag of the entire boat hull, a measurement that combines surface smoothness and surface area. If you feel this problem is too open-ended for your students, you may want to define the issue more precisely.

Prototype Construction and Evaluating Design

This last exercise should pull together the concepts covered in all preceding activities. On the one hand, student teams should be given as much freedom as possible to design and build the best boat they can. On the other hand, students should understand that they need to be using the knowledge gained from previous activities and not attempt to improve performance based on completely new variables (such as a large motor). Laboratory Journals should be referenced on previous activities and ideas.



Communication

3 DAYS

OVERVIEW—COMMUNICATION

You have met the challenge. You have redesigned a boat hull and you have built and tested a model boat that has improved performance over the Quick-Build. It has taken you some time and much effort, but until you communicate the importance of your work to the people who matter, your efforts will have little meaning. Indeed, one of the most critical abilities today is to be able to communicate clearly, effectively, and persuasively.

As an engineer, scientist, or developer, you are dependent on funding from private and public foundations. It is important to convince those with money why they should give support to the work you do. You may want to present your ideas to local officials or create a Web page that would make your work accessible to the entire world. There are individuals and companies in the boat-building industry, who are very interested in new designs or marketing their boats to the consumers. Publications are also important for communicating your findings to the greater scientific community.

Think about the discoveries you have made with the *Construct-a-Boat* challenge. Communicate the important parts of what you have done to several different audiences, including your classmates, a group of novice boat builders, and most importantly, yourself. Think about the interests your audience might have in your work. Recognize that there are many possible formats to communicate with your audience, and select one or more formats to present your work.

Scope of Work

- Create a project report that communicates the results of your work. Your target audience may be executives of a boat-building company or people attending a trade show.
- Present your redesigned model boat, including the rationale, substance, and outcomes of your effort.
- Complete the post-challenge assessment, and reflect on what you have learned in this challenge module.

CREATING A PROJECT REPORT

The final activity of this unit is for you to communicate the results of your work in a project report. Your goal is to include information that will inform builders of full-sized boats about the capabilities of your design.

An important skill for you to demonstrate in your project report is the ability to communicate clearly in writing. The writing of each section should be well organized and clear enough for someone unfamiliar with your design to understand.

Have fun thinking about ways to creatively describe your model design. Consult the table of contents below for a list of the topics you should address in your project report.

Model Boat Project Report

I. Project Statement

II. System Overview
  A. Physical Specifications
  B. Performance Specifications

III. Research

IV. Development

V. Supporting Data

Members of your team should divide the responsibility for each of the sections that need to be written. Before you do so, read the suggestions below to obtain a clear idea of what each section is about.

PRESENTATION

In meeting the *Construct-a-Boat* challenge, you redesigned a boat hull and built a model boat for improved performance. You have kept careful records (perhaps even photographs) and you have the prototype model for display. You are now asked to give an oral presention to an objective audience on the rationale, substance, and outcomes of your effort. You have limited time for your presentation, so do some careful planning and rehearsal. This should be a team effort, with each team member responsible for communicating a key part of the presentation. Expect to field questions from your teacher and audience. You may find visual aids useful in presenting key data and in providing your audience with tools for quick and clear analyses.

Prepare an outline of key points to cover. Focus on capturing your audience's interest, but clearly identify the strengths and distinguishing features of your design, as compared with those in other team presentations. Present the evidence that the design accomplished its purpose by quantitative and qualitative comparisons to the Quick-Build, using the criteria developed previously by the class.

List your preliminary presentation outline with team member assignments below. Consult with your teacher as a resource in your planning.

Presentation Outline	Team Member Assigned
TITLE:	
I.	
II.	
III.	
IV.	

REFLECTION AND RECOMMENDATIONS

Set forth at least five prioritized factors to consider, design criteria, or statements of wisdom you would offer to others who would be interested in designing and building a high-performance boat.

Make your recommendations based on the experience and knowledge you have gained through research, development, and testing of your own model boat, and through comparing your results with those of other teams.

- Using a model of causal relationships, describe two key factors you enhanced to improve performance.

- What do you recommend about working with performance evaluation before beginning your important design work?

SNAPSHOT *of Understanding:*

What I *now* know about models, systems, and design.

1. What are some of the factors that would have significant effects on the speed and acceleration of a model boat?

2. Do these factors have any effect on each other? If so, what might those effects be?

3. What are models used for?

4. What is a system?

5. Describe your project and list your major process stages from concept to finish.

6. Describe an experiment that determines which of two boats has greater acceleration.

MATERIALS

FOR EACH STUDENT

Student Activity Sheets

- Overview—Communication
- Creating a Project Report
- Reflection and Recommendations
- Snapshot of Understanding

FOR EACH TEAM

- *Presentation aids (select from options):*
- *overhead projector*
- *flip charts*
- *computer displays*

PREPARATION

- *Prepare a presentation event plan, location, and agenda.*
- *Consider offering spectator invitations.*
- *Provide students with examples of project reports.*
- *Arrange for use of word processing/graphics (or CAD) computer stations.*
- *Prepare a grading plan for your evaluation of the team and individual effort.*
- *Customize the project report table of contents to fit the time and educational objectives for your class.*

3 DAYS

OVERVIEW—COMMUNICATION

Student teams summarize their learning by creating a product prospectus that includes information about specific applications for their model boat, its construction, hull shape, factors influencing the performance, and performance parameters.

In the final assessment, students answer questions similar to those at the very beginning of the unit by retaking the *Snapshot of Understanding*.

Time Requirement

Devote one or more classes to team preparation of the reports. Presentation of the reports should be strictly timed so that all teams can report within the allotted time (one or two days, depending on class size).

Devote one class to reflection on the process and final self-assessment.

TEACHING SUGGESTIONS

Preparing the Report

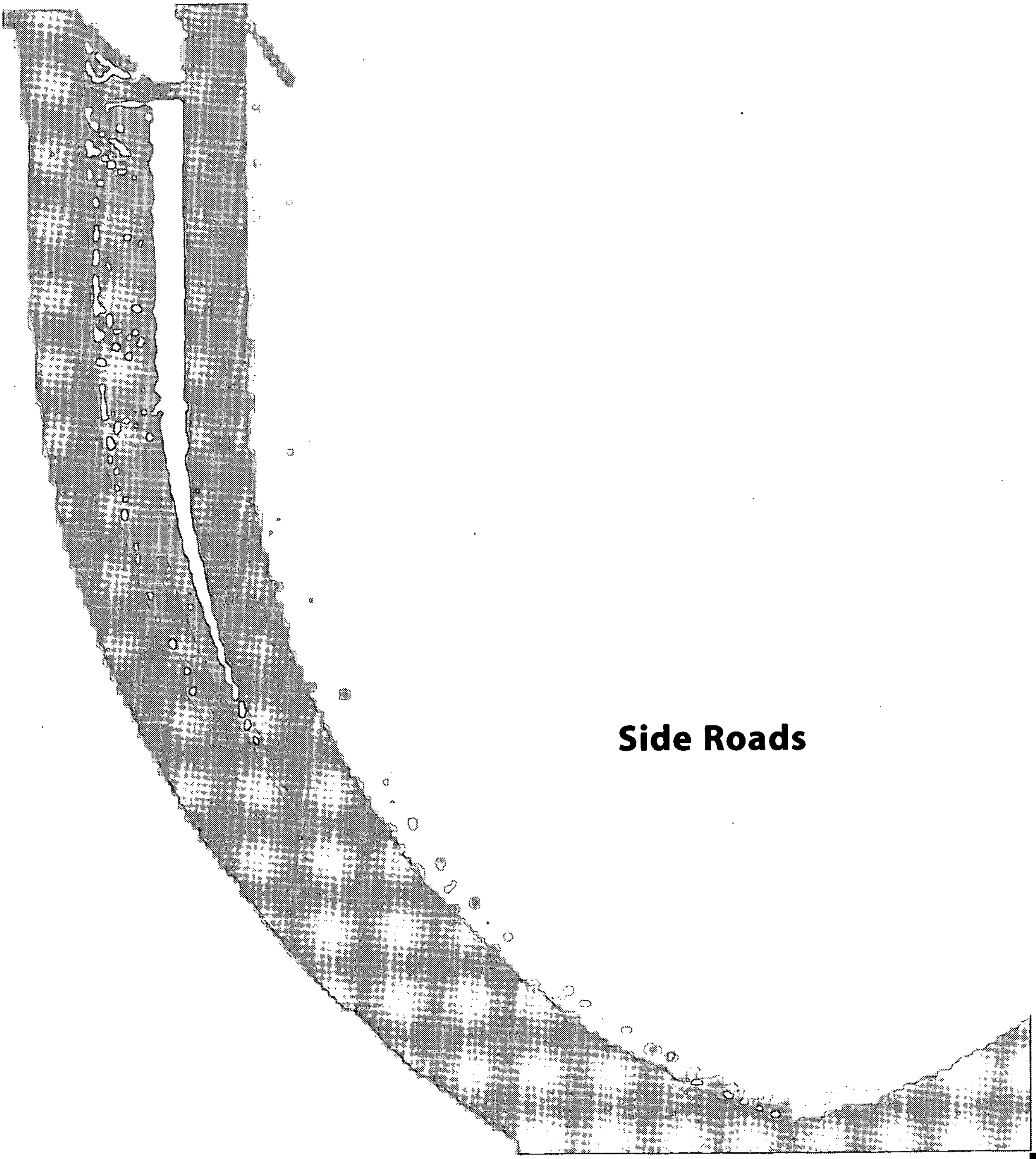
Teams should divide preparation and presentation responsibilities among members so that effort and benefits of the work and learning are distributed equitably. An assessment rubric, tailored to fit your class learning and evaluation objectives, should be made available to teams well in advance—possibly at the beginning of the prototype development phase—to encourage maximum awareness, planning, and preparation.

Presentation

Fitting a presentation into the time allotted is a skill few speakers ever master. You will need to warn all teams of the importance of staying within their time slot and you will need to be strict in enforcing time limits. If you invite visitors to the presentations, they will need to be informed of your time limits and of the kind of input you would like them to provide.

Completing the Snapshot of Understanding

After students complete the final *Snapshot of Understanding* (allow about 20 minutes), provide a brief period of time for them to compare their new answers with those on their pre-unit *Snapshot*.



Side Roads

SIDE ROADS

The material on the following pages is intended to support additional activities that you may choose to add to those described in the core course. Many of these are key activities, but they have been put in the Side Roads section because they can fit in several different places in *Construct-a-Boat*—you can decide exactly when to use them in response to student questions and feedback. Some activities may be used (profitably) more than once. An analysis of the design process, for example, will provide different insights when used in the research activities, than when used in the development activities.

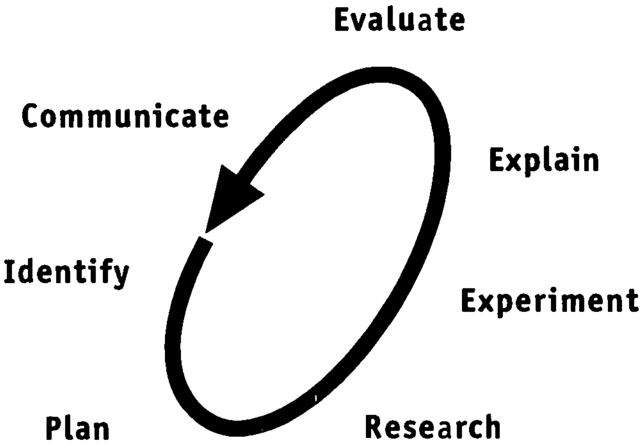
Two optional *Snapshots of Understanding* are included. One can be used to evaluate students' grasp of the concept of a model; the other to evaluate student understanding of control of variables. Construct-a-Boat assumes that students understand these concepts. You will need additional materials if their understanding proves to be weak.

In this section:

- *Inquiry Process*
- *Modeling Design Solutions*
- *Design Process*
- *Charting a Mathematical Model*
- *Simulating Model Calculations*
- *Snapshot of Understanding: Models*
- *Snapshot of Understanding: Control of Variables*

INQUIRY PROCESS

The *inquiry process* is often viewed as a cycle of action that repeats until the investigators reach a satisfying solution. It can be described with seven basic elements:



Identify and clarify questions. Understand the issue or problem, and make a testable hypothesis.

Plan appropriate procedures. Brainstorm, draw and write ideas, clarify their ideas, and suggest possible strategies or methods.

Research major concepts. Learn what is known about the situation from sources other than actual investigation, and obtain information from preliminary experiments. Decide what technology, approach, equipment, and safety precautions are useful. Document your experiments and log your data.

Experiment. Use tools and measuring devices to conduct experiments. Use calculators and computers to store and present data.

Explain logical connections. Analyze your data. Formulate explanations using logic and evidence, and possibly by constructing a physical, conceptual, or mathematical model.

Evaluate alternatives. Compare your explanations to current scientific understanding and other plausible models. Identify what needs to be revised, and find the preferred solution.

Communicate new knowledge and methods. Communicate results of your inquiry to your peers and others in the community. Construct a reasoned argument through writing, drawings, and oral presentations. Respond appropriately to critical comments.

SCILINKS®
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Topic: scientific inquiry
Go to: www.scilinks.org
Code: CAB08

Questions

Read the following questions, but do not answer them until after your team has experienced working together on the design challenge research activities.

1. Make your own checklist of team activities that correspond to steps in the cycle described above:

2. Create your own version of the inquiry process using words and pathways that fit your team's activity.

3. What shape is your inquiry pathway diagram (circle, spiral, cascade, other)?

4. How and where do the seven steps described above fit within your process description?

MODELING DESIGN SOLUTIONS

Defining Modeling

Modeling is the activity of imitating reality. You can use modeling to simulate actual events, structures, or expected conditions to test, analyze, and refine your design ideas. You also use models to focus on important parts of the total problem.

In *Construct-a-Boat,* we use different types of models:

- **Graphic Models**
  Typical graphic models are conceptual drawings, graphs, charts, and diagrams. Conceptual drawings capture the designer's ideas of specific details; graphs and charts display numerical information and help the designer assess results; and schematic diagrams show relationships between components. You have already made and used several graphic models.

- **Physical Models**
  A physical model is a three-dimensional representation of an actual object. You can construct a physical model with materials that are easy to work with, such as wood, clay, polystyrene, and paper. Because full-size models are often impractical, people use *scale models* to show how a product will look or to test the operation of a system. A scale model is proportional to actual size by a ratio. Your Quick-Build is a physical model.

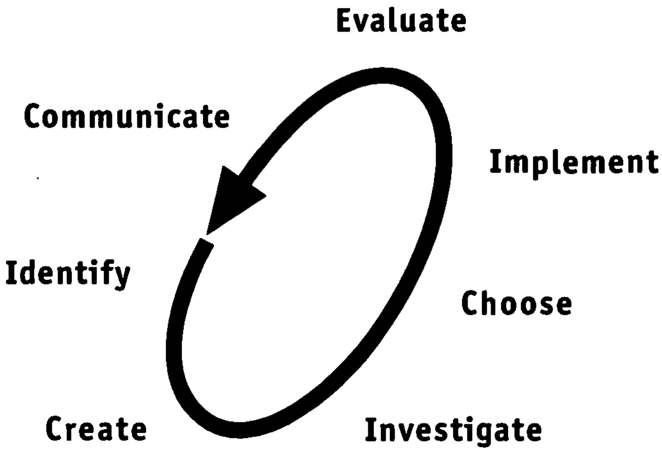
- **Mathematical Models**
  Mathematical models show relationships in terms of formulas. For example, the formula for speed shows the relationship between the distance traveled by a boat and the time it takes to travel that distance:

  $$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

  In general, you would need to use many formulas and inter-relate them to predict the results of more complex relationships.

DESIGN PROCESS

The design process is often viewed as a cycle of action that repeats until the designers reach a satisfying solution. It can be described with seven basic elements:



Identify and clarify the situation. Understand the challenge or problem, including the criteria for success and constraints on the design.

Create solutions. Brainstorm, draw and write ideas, and suggest possible strategies or methods.

Investigate possibilities. Learn what is known about the situation, and what technology or approach could be useful. Conduct experiments to test your ideas.

Choose a solution. List the solutions most likely to be successful, and make decisions for how well each solution meets the design challenge or solves the problem.

Implement the design. Learn that a successful design often depends on good fabrication, whether it is a scaled or life-sized version of the product.

Evaluate the design. Perform tests to obtain the feedback that informs them about the parts of the design that worked or needed improvement.

Communicate the solution. Present your designs to your peers and others in the community, communicating your ideas through drawings, writing, formal presentations, informal discussions.

Questions

After reading about the design process, answer the following questions:

1. What elements of the process have you already experienced?

2. What elements have you not yet experienced?

3. Where in the process do you think you are now?

4. What will your next steps be?

CHARTING A MATHEMATICAL MODEL

In order to study how various factors influence your boat's speed and acceleration, you need a way to look at several factors acting at once. A chart can be a useful way to do this.

Study the chart below and fill in the incomplete cells.

Factor	What does it depend on?	What does it affect?	How would you control it?
mass	*building material, size of boat, load being carried*	*acceleration (speed change)*	*choose different kinds of material, work on size of boat*
force of motor (thrust)	*batteries, type of propeller, size of motor*	*acceleration*	
force of friction (drag)			
acceleration (speed change)			

Quantifying the Chart

With your factors now in place and with a qualitative feel for how they relate to each other, you can start to see how they affect each other quantitatively. Because the boat starts with no speed and must accelerate up to its maximum speed, you need to examine acceleration. The fundamental law for acceleration is Newton's Second Law: $F = ma$.

First, look carefully at the three components of this equation. There are two main forces acting on our boat. The force of the motor and the resistance or friction force of the water. There is one mass, the mass of the boat. There is one acceleration, the acceleration of the boat.

The work sheet Fluid Friction Dynamics on page 41 described an equation for the friction force, it was: $F_{friction} = k v^2$ where k is made up of two parts: C, a measure of roughness; and A, the total surface area in the water. Because neither C nor A changes as the boat moves through the water, consider their product k as a constant number. (In hydroplanes, A does change as the boat moves but you are not working with that kind of boat.)

The equation for $F_{friction}$ has the value zero when the speed is zero. You can now fill out the first column of the chart on the next page.

Use the letter M to stand for the mass of the boat; you will need to weigh yours to get a number. Enter that mass (M) all across the row because it will not change.

Use the letter F to stand for the force of the motor (see unit of measuring the force of the motor). Enter that all across the row because it will not change.

Time in seconds	0	1	2	3	4
Mass	___ g	___ g	___ g	___ g	___ g
Force of motor (thrust)	F	F	F	F	F
Force of friction (drag)	0				
Total force	F				
Acceleration	F/M				
Speed	0				

SIMULATING MODEL CALCULATIONS

To fill in the second column of the table on page 74, it may be helpful to work in teams of five. Each person takes a turn at calculating a value for the table. We will work up from the bottom row. Remember that the values you are calculating are relationships in a mathematical model, not necessarily numerical values.

1. The first person determines, from team data, the speed change:

   The speed change value equals: $\dfrac{\textbf{(thrust - drag)}}{\textbf{mass}}$ **x time interval**

2. The second person calculates the new speed:

   new speed = old speed + speed change

   Enter this result for the next value of speed.

3. The third person, using team data again and the calculations above, determines the new acceleration.

   That value will equal: $\dfrac{\textbf{total force}}{\textbf{mass}}$

   Enter this result for the new value of acceleration.

4. The fourth person calculates the friction of the water:

   drag = friction coefficient x wet surface area x $\textbf{(speed)}^2 = \textbf{k (speed)}^2$

   Enter this result for the next value of force of friction.

5. The fifth person calculates the total force:

   The total force will be equal to: **(thrust - drag)**

   Enter this result for the new value of total force.

Now that you have the second column filled, it is time to move to the third column. The first person repeats the calculation using numbers from column two.

Your group can continue this process until the boat reaches maximum speed.

Checking Your Intuition

You have completed one worksheet. This data should help you see how design changes might affect the performance of the boat. What would happen if you made the boat lighter?

Use your intuition to complete the following sentences with one of these choices: increases, decreases, does not change.

1. As the mass of the boat increases, the top speed .....
2. As the mass of the boat decreases, the top speed .....
3. As the motor-force increases, the top speed .....
4. As the motor-force decreases, the top speed .....
5. As the wet surface area increases, the top speed .....
6. As the wet surface area decreases, the top speed .....
7. As the gliding surface roughness increases, the top speed .....
8. As the gliding surface roughness decreases, the top speed .....

Predicting the Effects of Design Changes

Using the chart calculation, you can see the effect of possible changes you might make to your boat's design. You can actually determine how a certain change will affect the time that it takes to reach top speed.

If you know how to use a spreadsheet program, you can use it do the work of the five people and create a chart that fills in automatically.

Here are some design changes to consider:

What happens when you make the gliding surface half as rough? How would you use such information to help you redesign and build your boat hull?

How big a change would you need to make in the wet surface area to get as big an effect as you got cutting the roughness in half?

How much would you need to change the mass of the boat to get this effect?

SNAPSHOT *of Understanding:* MODELS

Give three different examples of models.

What are models used for?

What is important to include in a model?

Can there be more than one model for the same thing?

SNAPSHOT
of Understanding:

CONTROL OF VARIABLES

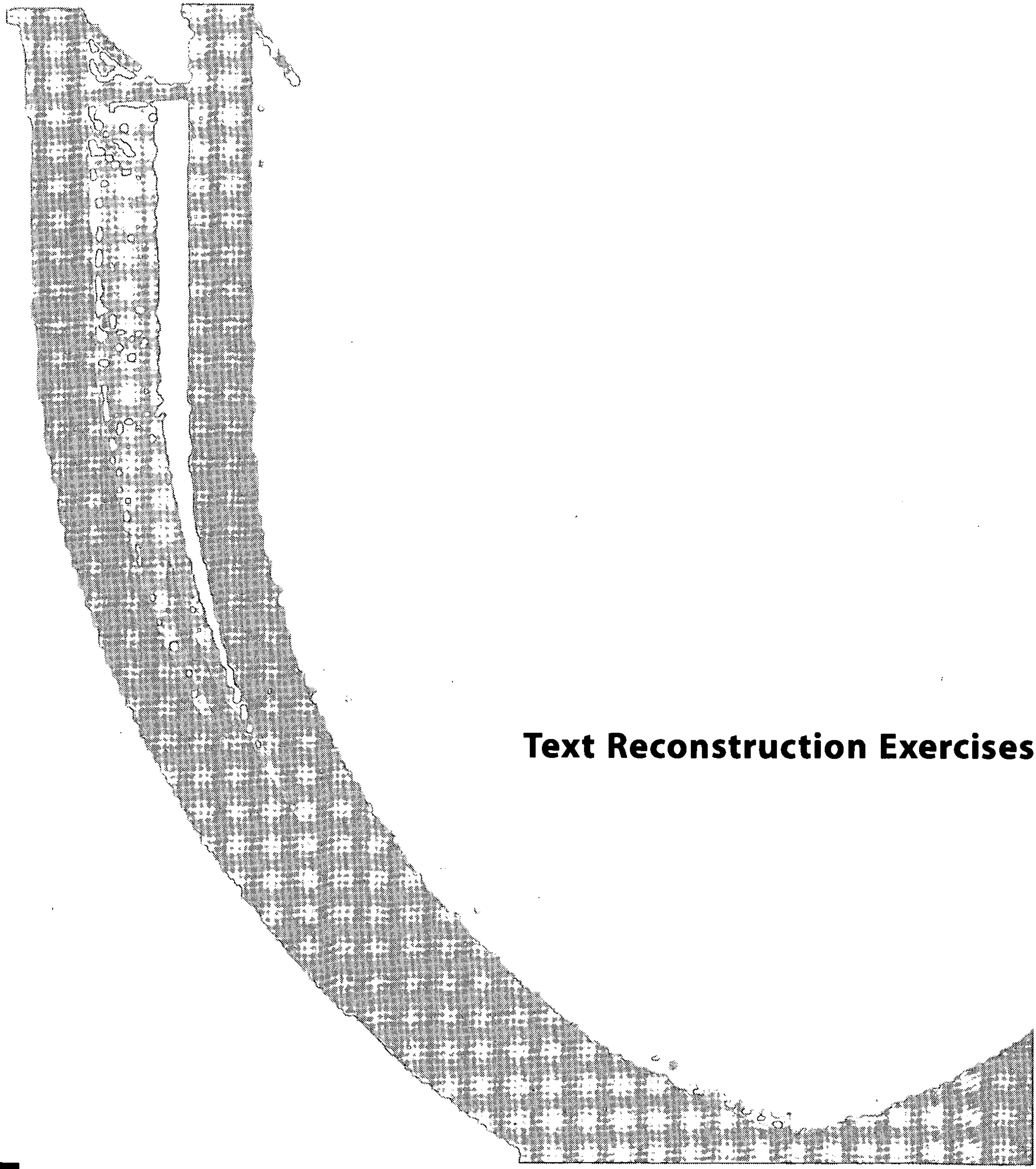
Two companies are conducting experiments to understand how to build a better canal system. Each company built two canals to learn how canals affect boat speed.

The first company built one canal that was narrow and shallow, and another canal that was wide and deep.

The second company built one canal that was narrow and deep and another canal that was wide and deep.

Which company designed the better experiment? Why?

Appendix B



Text Reconstruction Exercises

TEXT RECONSTRUCTION

The jumbled paragraphs in the following reading assignments are examples of Text Reconstruction (TR). This well-established technique for reading and writing improvement has roots going back to Benjamin Franklin as well as a number of famous authors. Many teachers find that including TR in a reading assignment highly motivates students and results in a much higher rate of homework completion. We suggest you read Chapter 5 of *Why Johnny Can't Write* for complete instructions on how to design your own exercises. Additional exercises can be found in *How to Analyze, Organize, & Write Effectively.*

An instructional process that uses design or inquiry places great demands on class time. It is impossible to cover all essential content within the few hours per week students spend in class. Science and technology courses must therefore insist that students learn from reading. This means they must also provide realistic opportunities for students to improve their ability to learn from reading.

Text Reconstruction works as a method of improving reading skills by focusing student attention on the most important elements of the reading task. First, it changes the reader's perception of his or her role from that of a passive absorber of information to that of an active agent who must sort out a puzzle. This is probably the main reason TR exercises are popular with students. Secondly, TR forces students to pay attention to the logic of a paragraph. In science, it is not the separate ideas that are important, but rather the logic that ties them together. When passively reading a paragraph, one can easily miss that logic, but in TR it is impossible to complete the task without thoroughly understanding these interconnections. A student who reconstructs a paragraph will understand its structure and meaning far more deeply than a student who memorizes every word but considers them only in their current order.

In the *Science by Design* series, we employ various techniques to encourage student reading and writing. These are not extras, but rather essential elements of the program. The exercises included assume that your students are relatively strong readers. If your students are weak readers or are not used to serious homework, then you will need to increase the amount of attention you pay to improving reading skills. Text Reconstruction can be used to convert any kind of reading assignment into a stimulating puzzle. The more use you make of TR, the more your students will read and the better they will understand.

For more information on Text Reconstruction Across the Curriculum contact: The Institute for TRAC Research, P.O. Box 7336, Albuquerque NM. Tel. (505) 831-2654 or visit the New Intelligence *Web site at http://www.newintel.com*

FORCES, SPEED, AND ACCELERATION TEXT RECONSTRUCTION EXERCISE

The paragraphs below describe important information about forces, speed, and acceleration. To keep this information confidential, some of the sentences within each paragraph have been reordered. Your task is to restore them to their proper order.

Forces, Speed, and Acceleration

¶1

____ Despite impressive mathematical accomplishments, the Greeks never understood the connections.

____ The relationship of force, speed, and acceleration eluded scientists for most of recorded history.

__4__ Even then, it took Newton over 20 years to develop his three simple laws.

____ It was not until Newton's efforts a mere 350 years ago that a perspective consistent with our modern view emerged.

¶2

____ How can something as simple as Newton's Laws be so confusing?

____ We therefore conclude that speed and force are related.

__2__ The confusion stems from our common experience of pushing and pulling.

____ In that experience, it takes force to make things move, and more force to make them move fast than to make them move slowly.

¶3

____ Here is a way to think about it.

____ But in Newton's view, speed and force are not related!

____ In Newton's famous Second Law, force is related to acceleration: the *change* in speed.

¶3 cont.

3 But why isn't the change in speed related to speed?

____ How much you eat for dinner tonight is related to how much your
____ weight will increase or decrease.

6 But even if I was told what you ate for dinner every night from the day you were born, I could not figure out how heavy you are.

¶4

____ Yet if I get on my bicycle I know this is wrong.

____ Thus in Newton's picture of the world, force tells us about acceleration—the change in speed—but it cannot tell us about speed itself.

____ I have to pedal harder to go faster.

____ But the reason I have to pedal harder is because of air resistance.

____ Instead of pedaling harder, I could reduce my air resistance by getting racing clothes, or by cycling behind an air shield.

____ Then I would go fast without pedaling harder.

____ Thus a cyclist can go faster without increasing the force exerted.

SYSTEMS TEXT RECONSTRUCTION EXERCISE

Systems

¶1

____ Understanding those effects and relations is called *systems analysis*.

____ Systems analysis and systems thinking are increasingly important aspects of the modern world.

2 In any complex situation, there are many related parts which affect each other.

¶2

____ The simplest kind of systems analysis involves understanding whether an increase in one quantity will cause an increase, decrease, or no change in another quantity.

____ If you increase what you eat for dinner, you will increase your weight (unless you also exercise more, or do something equivalent).

¶3

____ Often the links in a systems analysis can be complicated and even contradictory.

____ But when the weather gets colder, it also snows more and so you go skiing and get more exercise.

2 If the weather gets colder, you play less baseball and get less exercise.

¶4

____ In a simple case, we can tell what will happen without having to calculate with numbers.

2 It snows and I will go skiing.

____ To calculate the exact amount of exercise for each case, I will need to use a mathematical model.

____ But will I get more exercise than I got back in July?

____ Here I will need to know how many times I played baseball, how many times I went skiing and how much exercise I got each time.

MODELING TEXT RECONSTRUCTION EXERCISE

The paragraphs below describe important information about modeling. Your task is to restore these jumbled paragraphs to their proper order.

Modeling

¶1

____ Our case is just the opposite.
____ The word "model" has several different meanings.
____ We will use it in the following way.
4 This is different than the most common usage of the term, in which "model" really means "looks like."
____ A model is a device that acts like the thing it is a model of, but is not itself that thing.
____ A model car looks like a car, but it does not run like a car.
____ Our model boat does not look much like a boat, but it does run like a boat.

¶2

____ Modeling is the process of making models that behave like the thing we are modeling.
____ Some models are physical.
____ We can touch them, move them, and measure them.
5 A mathematical model for the speed of our boat would give bigger or smaller numbers depending on whether the boat's speed is getting bigger or smaller.
____ The speedometer on your car is, in this sense, a model for your car's speed.
____ The clock in your computer is a mathematical model for time.
____ On the other hand, the spring-driven wristwatch your grandfather used to have is a physical model of time.
____ Other models are mathematical.

93

_2_ Computer modeling is becoming increasingly important to us because in many cases, it is cheaper, quicker, and safer to make a computer model than to make a physical model or to test the real object.

____ In the 1950s and 1960s, many pilots were killed testing new kinds of airplanes.

____ Today, airplanes are tested as mathematical models before they are even built, and far fewer pilots are killed testing them.

____ Building mathematical models using computers is called *computer modeling*.

FORCES, SPEED, AND ACCELERATION TEXT RECONSTRUCTION KEY

The paragraphs below show the correct order of sentences in the Forces, Speed, and Acceration text reconstruction exercise. When you hand out the initial homework assignment, ask students to number the sentences in each paragraph so as to put them in the correct order. It is also highly beneficial to ask students to rewrite the paragraphs once they have determined the correct order.

Paragraph 1

1. The relationship of force, speed, and acceleration eluded scientists for most of recorded history.
2. Despite impressive mathematical accomplishments, the Greeks never understood the connections.
3. It was not until Newton's efforts a mere 350 years ago that a perspective consistent with our modern view emerged.
4. Even then, it took Newton over 20 years to develop his three simple laws.

Paragraph 2

1. How can something as simple as Newton's Laws be so confusing?
2. The confusion stems from our common experience of pushing and pulling.
3. In that experience, it takes force to make things move, and more force to make them move fast than to make them move slowly.
4. We therefore conclude that speed and force are related.

Paragraph 3

1. But in Newton's view, speed and force are not related!
2. In Newton's famous Second Law, force is related to acceleration: the *change* in speed.
3. But why isn't the change in speed related to speed?
4. Here is a way to think about it.
5. How much you eat for dinner tonight is related to how much your weight will increase or decrease.
6. But even if I was told what you ate for dinner every night from the day you were born, I could not figure out how heavy you are.

Paragraph 4

1. Thus in Newton's picture of the world, force tells us about acceleration—the change in speed—but it cannot tell us about speed itself.
2. Yet if I get on my bicycle I know this is wrong.
3. I have to pedal harder to go faster.
4. But the reason I have to pedal harder is because of air resistance.
5. Instead of pedaling harder, I could reduce my air resistance by getting racing clothes, or by cycling behind an air shield.
6. Then I would go fast without pedaling harder.
7. Thus a cyclist can go faster without increasing the force exerted.

SYSTEMS TEXT RECONSTRUCTION KEY

Paragraph 1

1. Systems analysis and systems thinking are increasingly important aspects of the modern world.
2. In any complex situation, there are many related parts which affect each other.
3. Understanding those effects and relations is called *systems analysis*.

Paragraph 2

1. The simplest kind of systems analysis involves understanding whether an increase in one quantity will cause an increase, decrease, or no change in another quantity.
2. If you increase what you eat for dinner, you will increase your weight (unless you also exercise more, or do something equivalent).

Paragraph 3

1. Often the links in a systems analysis can be complicated and even contradictory.
2. If the weather gets colder, you play less baseball and get less exercise.
3. But when the weather gets colder it also snows more and so you go skiing and get more exercise.

Paragraph 4

1. In a simple case, we can tell what will happen without having to calculate with numbers.
2. It snows and I will go skiing.
3. But will I get more exercise than I got back in July?
4. Here I will need to know how many times I played baseball, how many times I went skiing and how much exercise I got each time.
5. To calculate the exact amount of exercise for each case, I will need to use a mathematical model.

MODELING TEXT RECONSTRUCTION KEY

Paragraph 1

1. The word "model" has several different meanings.
2. We will use it in the following way.
3. A model is a device that acts like the thing it is a model of, but is not itself that thing.
4. This is different than the most common usage of the term, in which "model" really means "looks like."
5. A model car looks like a car, but it does not run like a car.
6. Our case is just the opposite.
7. Our model boat does not look much like a boat, but it does run like a boat.

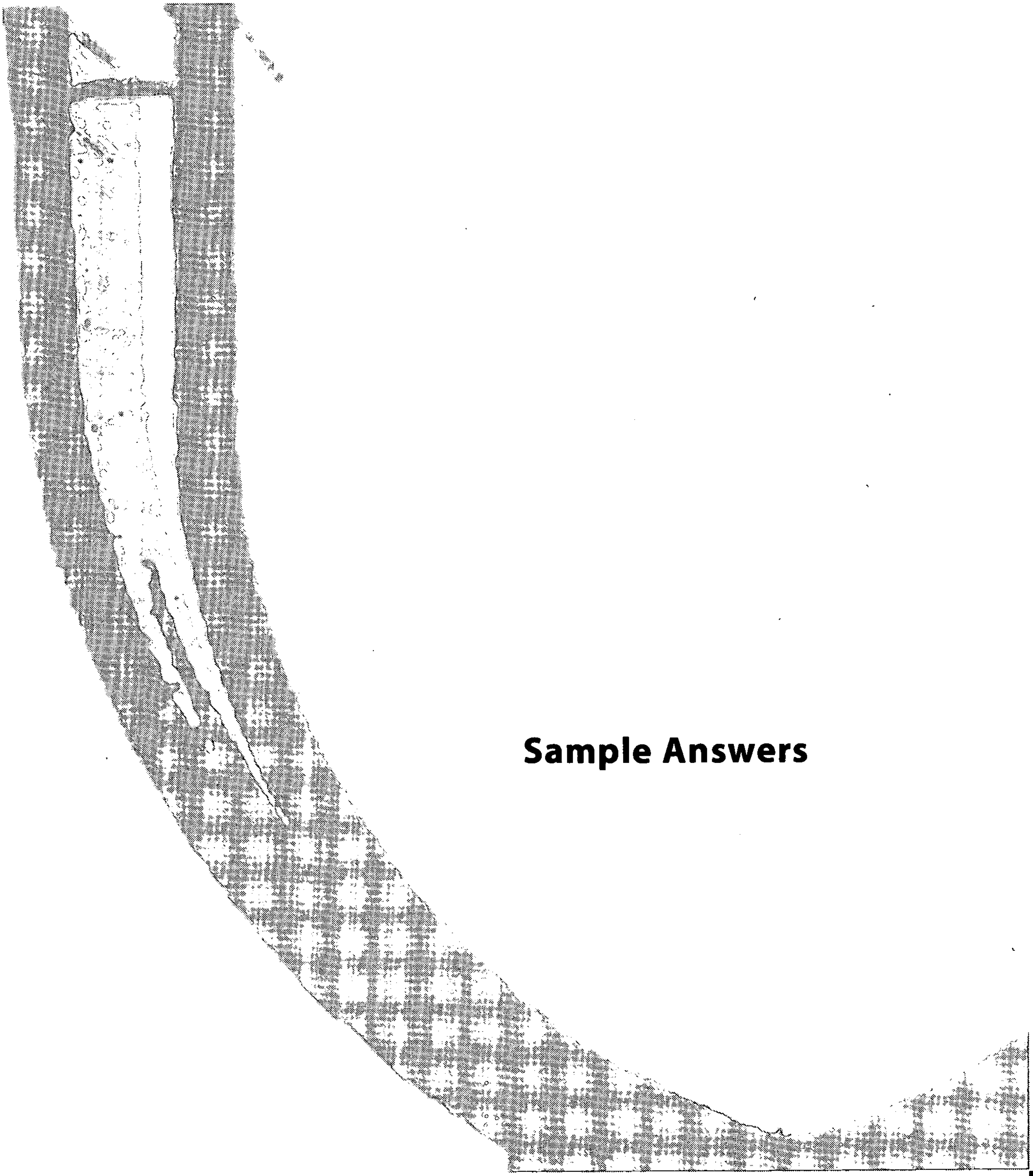
Paragraph 2

1. Modeling is the process of making models that behave like the thing we are modeling.
2. Some models are physical.
3. We can touch them, move them, and measure them.
4. Other models are mathematical.
5. A mathematical model for the speed of our boat would give bigger or smaller numbers depending on whether the boat's speed is getting bigger or smaller.
6. The speedometer on your car is, in this sense, a model for your car's speed.
7. The clock in your computer is a mathematical model for time.
8. On the other hand, the spring-driven wristwatch your grandfather used to have is a physical model of time.

Paragraph 3

1. Building mathematical models using computers is called *computer modeling*.
2. Computer modeling is becoming increasingly important to us because in many cases, it is cheaper, quicker, and safer to make a computer model than to make a physical model or to test the real object.
3. In the 1950s and 1960s, many pilots were killed testing new kinds of airplanes.
4. Today, airplanes are tested as mathematical models before they are even built, and far fewer pilots are killed testing them.

Appendix C



Sample Answers

Activity 3, p.32

ORGANIZING THE DATA

Here is an example of recording and calculating data for the change of speed over time.

Time on stopwatch (in seconds)	Distance from starting point (in meters)	Speed @ distance (in m/s)	Speed change = $\text{speed}_n - \text{speed}_{n-1}$ (in m/s)
0 (start)	0.00	0	0
3	.06		
6	.22		
9	.47		
12	.75		
15	1.07		
18	1.39		
21	1.72		

Students should be encouraged to find their own way to calculate speed, but their thinking needs to be pushed and challenged. Their first ideas are likely to be wrong. Mindless use of speed vs. distance/time will generate incorrect answers!

Here are some approaches that work:

1. Graph the data for distance vs. time and calculate speed from the slope of the graph. Graphing calculators work well here.

2. Calculate the average speed to that point in time. If the accelerations were constant, speed at the end time would be twice the average speed over the interval.

3. To improve on Method 2, calculate the average speed over the time interval. Compare that to the speed at the end of the previous interval and use twice the difference for the speed at the end of the interval. This method only assumes constant acceleration over the time interval, and is quite accurate for small time intervals.

SCALE MODEL EXTENSIONS HOMEWORK

Activity 3, p. 40

1. Use the Weight Scale Factor to calculate the weight for the model boat based on the Design Brief data for a real boat with no cars or people.

   Scale factor = 12,167,000
   M/V Nantucket = 1150 tons = 2,300,000 lbs
   Model = 2,300,000/12,167,000 = 0.189 lbs = 80 grams
   Model Boat Weight = 80 grams

2. Estimate the maximum weight of people and cars that the ferry carries.

   1100 people x 125 lbs/person - 137,000 lbs
   60 cars x 3000 lbs/car = 180,000 lbs
   People and Cars Weight = 317,000 lbs

   Determine the scale weight for people and cars in *grams.*
   317,000 lbs/12,167,000 = .026 lbs = 13 grams
   People and Cars Scale Weight = 13 grams

MINIMIZING SURFACE AREA

Activity 3, p. 43

Fill with Sand

Questions 1–2 are procedural

3. Compute the total area of the inside surface that touched the sand. Note the units you use for area.
   Method 1: Lay a grid over the "wet area" and count squares

   Method 2: Divide "wet area' into geometric shapes and calculate area of each shape from length measurements and geometry

4. What is your conclusion about the relationship between volume and surface area?
   Some shapes have more volume per unit surface area; curved surfaces seem to have the highest

5. How will this information help you in the design of the boat hull?
   Can help design for reduced friction

Activity 4, p. 51

BUILDER PROBLEM

Propose *two* distinct methods to minimize fluid friction and describe them in the space below. Use additional pages for sketches if that helps your explanation.

One involves reducing wet area; another involves reducing surface roughness.

Design and conduct a test to determine improvements in the friction coefficient for the model boat. If you can, try using the computer model to understand better how the friction coefficient affects the model boat performance. Describe your test below.

There are many solutions. One involves pulling the boat with a spring scale. But be careful: results depend on speed. It is difficult to pull a boat at a constant speed

Activity 4, pp. 52–55

PROTOTYPE CONSTRUCTION

Proposal

Review student work to look for designs with reduced wet area and designs with smoother finish. Check that their plans are consistent with available fabrication skills and facilities.

Materials

Review student lists for completeness and consistency with any material limitationsyou have stated.

Comparing Performance Data

1. top speed of Quick-Build = *.5 m/sec*
   top speed of new model = *.6 m/sec*
2. acceleration time for Quick-Build = *10 sec*
   acceleration time for new model = *10 sec*
3. Compare the performance of your new model to that of your Quick-Build. Provide a brief qualitative description below.
   Example: *The new model is slightly faster, about 20%*
4. How would you describe the improvement in performance quantitatively? What calculations do you need to make?
   Example: *We will need to repeat baseline measurements and organize the data. We will need to devise a speed vs. time graph and compare it to the baseline original.*
5. Summarize your results and explain how you have achieved them.
   Example: *We reduced water/friction, increasing both the average acceleration and the top speed. We did this by changing the hull shape and by reducing the surface roughness.*

baseline data: data taken to determine conditions before an experiment is started

beam: the widest point of the hull at the waterline

brainstorm: a group problem-solving technique that involves the spontaneous contribution of ideas from all members of the group

calibration: determining a measurement scale or aligning a device with a measurement scale

centerline: the line of a boat running fore and aft (see **keel**)

draft: the distance from the waterline to the lowest part of the hull; the draft determines the shallowest depth in which the boat will still float

dynamics: a branch of physics related to the effects of forces

energy conversion: energy in different forms is often converted from one form to another; heat is converted into light, light into heat, motion into heat, etc.

energy transfer: the movement of energy from one place to another or from one form to another

equilibrium: a balance between two opposing processes such that the net effect of the two processes is no total change. For example, we breathe in about as much air as we breathe out, so that over time, our lungs stay roughly the same size

factors: the different elements out of which a whole object is made, often used to describe the different causes that lead to a particular outcome

forces: pushes and pulls

friction coefficient: a constant varying with the condition of surface that determines the size of the force of friction. The coefficient is usually measured experimentally because it is too complicated to determine from theory

frictional force: resistance caused by the passage of water across the hull surface

hull: the outside wall of a ship that begins at deck-level and goes down to the keel

keel: the centerline of a boat running fore and aft; the backbone of a vessel

prototype: an original model; the first full-scale and (usually) functional form of a new type or design of a construction

residual resistance: all resistance affecting a body's motion through the water except the frictional force. Includes air friction and wave-making

scaling: increasing or decreasing the size of something in such a way that all parts are in the same proportion as the original object

scale factor: a number that indicates how much smaller or larger one object is as compared with a specific copy of it

scale model: a copy of an object (usually smaller) made so that all components are in proportion to one another

section: the shape of a plane passing through the hull perpendicular to the centerline

section coefficient: the ratio of the area of a section divided by the area of a rectangular section having the same beam and draft. It is a measure of the relative fullness of a section, and permits the comparison of hulls of differing sizes and shapes

system: a collection of interacting components that work together as a unit

tolerance: the degree of accuracy demanded in a construction

total displacement: the total weight of a boat including passengers and cargo

variable: an object or quality of changeable value

wetted surface: that part of the hull in contact with the water when the hull is loaded to its **total displacement**

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