

Interactive Learning Tools for Undergraduate Thermodynamics

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Introduction

In the age of the Internet, technology permeates education; never before has so much information been available so quickly to so many. This phase of the information revolution has prompted unprecedented numbers of new on-line courses and course materials, and the content available increases in sophistication at the impressive rate of hardware and software evolution. The potential in all of this technology is clear, but, as educational theory has shown, technology and its products are most effective in education when guided by sound pedagogical objectives.

At the University of Toledo, the union of technology and pedagogy in the development of an undergraduate thermodynamics course has resulted in the Learning Tool.

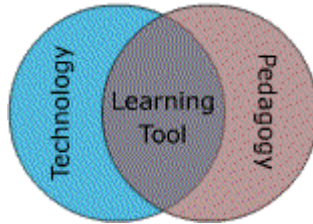


Fig.1. Intersection of Technology and Pedagogy

This project outlines the design of the Learning Tool, a group of multi-media components that present specific course concepts. The design of each Learning Tool component is guided by pedagogical principles to help students understand, learn, engage with, and retain course material. The components of the Learning Tool are designed to

1. deliver course materials through multiple modes (text, image, animation, etc.) to accommodate different learning styles;
2. provide different types of feedback (immediate, delayed, peer, instructor)¹;
3. prompt recall of important concepts to aid in long-term learning².

Learning Tool components and sequencing are designed with escalating levels of interactivity to help students progressively develop skills for all levels of competency in Bloom's Taxonomy of educational objectives: knowledge, comprehension, application, analysis, synthesis, and evaluation³.

Another important goal of this supplemental material is to escalate student engagement with course content. As shown by B. Shneiderman a conceptual framework for technology-based learning and teaching has emerged as an engagement theory.⁴ The fundamental idea underlying engagement theory is that students must be meaningfully engaged in learning activities through interaction with others and worthwhile tasks. While in principle, such engagement could occur without the use of technology, the technology can facilitate engagement in ways which are difficult to achieve otherwise.

Thermodynamics together with other thermal-fluid sciences (thermodynamics, fluid mechanics, and heat transfer) are typically considered to be among the most difficult topics taught in engineering curriculum.⁵ The Learning Tool described below is designed to improve the students understanding, learning, and enjoyment of this difficult subject matter.

The Learning Tool Structure

A group of multi-media components described below are brought together to create a Learning Tool. Because the analysis of thermodynamic cycles is one of the major topics in the undergraduate thermodynamics, the Learning Tool for the cycle analysis is chosen to illustrate the design, both in terms of content and pedagogy, of a typical Learning tool.

The course material for the semester consists of 6 chapters and presented with the table below

<u>Syllabus Course Schedule Instructor Information Glossary</u>	
1. <u>Entropy</u>	2. <u>Internal Combustion Engines</u>
3. <u>External Combustion Engines</u>	4. <u>Vapor Power Cycle</u>
5. <u>Refrigeration Cycles</u>	6. <u>Gas-Vapor Mixtures and Air Conditioning</u>

Each chapter contains one or several Learning Tools depending on the number of major topics in the chapter. For example, the External Combustion Engines chapter contains three major topics one of which is the Brayton Cycle. The Brayton Cycle Learning Tool is shown below as an example of a typical Learning Tool structure:

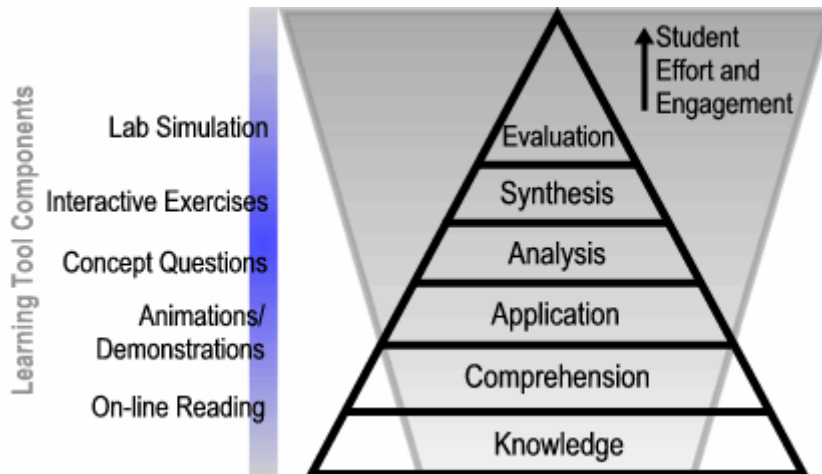
Brayton Cycle Learning Tool

<i>On-line Reading</i>	<u>Introduction/History</u>	<u>Ideal Cycle Analysis</u>	<u>Actual Cycle Analysis</u>	<u>Improving Efficiency</u> <u>Regeneration</u> <u>Intercooling</u> <u>Reheating</u>
<i>Animations/Demonstrations</i>	<u>How Gas Turbine Engines Work</u> <small>(from Rolls Royce website)</small> <u>Layout of the Gas Turbine</u> <u>Main Types of Gas Turbines</u>	<u>Value of the Carnot Cycle</u> <u>Ideal Cycle Diagram</u>	<u>Actual Cycle Diagram</u> <u>Actual Cycle Example</u> <u>Back Work Ratio</u>	<u>Actual Regenerative Cycle</u> <u>Example 1</u> <u>Example 2</u> <u>Regeneration with Reheating & Intercooling</u>
<i>Concept Questions</i>	<u>What are the Advantages and Disadvantages of Gas Turbine Engines?</u>	<u>Show that $T_3/T_2 = T_4/T_1$</u> <u>How does pressure ratio affect thermal efficiency?</u> <u>Enthalpy at the Actual Exit of a Turbine</u> <u>When to use the "Easy" Formula for Cycle Efficiency</u> <u>Why is Net Work Output an Important Factor?</u> <u>Compressor Work vs. Pump Work</u>	<u>Maximum Possible Heat Transfer in a Regenerator</u> <u>Effect of Decreasing the Lower or Increasing the Higher Temperature in the Cycle</u> <u>Why Intercooling Is Always Used with Regeneration</u> <u>How to Select Intermediate Pressure for Reheating/Intercooling</u>	
<i>Interactive Exercises</i>		<u>What Happens to η_{th} and W_{net} as the Pressure Ratio Increases?</u> <u>Isentropic Efficiency Exercise</u>	<u>Check that Regeneration is More Efficient at Low Pressure Ratios</u> <u>See Why Intercooling/Interheating is Effective</u>	
<i>Lab Simulations</i>	<u>Approximate vs. Exact Analysis of Ideal Gas Cycles</u> <u>Centrifugal Compressor Lab</u>			

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The Learning Tool structure presents the material related to the Brayton cycle in four *horizontal* categories: Introduction/History, Ideal Cycle Analysis, Actual Cycle Analysis, and Ways to Improve the Cycle Efficiency. The pattern of the Cycle Learning Tool is consistent throughout the course: the same four categories are used for every cycle considered in the course so the structure becomes familiar to the students. It helps them to establish the procedure for analyzing the cycles and thus to appreciate the similarity and differences between them. It also helps students to conceptualize the cycle in terms of this organization, and can learn how to work through the course material effectively by focusing on activities that best suit their learning style.

The *vertical* organization of the Tool also suggests a correlation to Bloom's taxonomy. As students work their way down through the levels of interactive components and exercises, they are effectively working their way up through the levels of the taxonomy. Also, as they progress through the components, an increasing amount of effort is required to engage the material. This complex dynamic is illustrated below:



The goals of this structuring of the Learning Tool and the components that comprise it are to

- a) facilitate student exploration of the subject;
- b) allow students to direct and manage their own study beyond the boundary of the classroom;
- c) stimulate student creativity and engagement by turning interest into action;
- d) give student an opportunity to learn by doing;
- e) establish a process of evaluative engagement by encouraging students to develop their own meaningful lab exercises.

Multi-media Components of the Learning Tool

Learning Tool teaching supplements contain four types of components: on-line readings, animated demonstrations, interactive objects, and lab simulations. The purpose of each component is presented below.

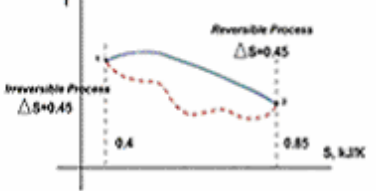
1. **On-line reading** material does not repeat but complements the textbook and emphasizes important concepts. The material is organized to allow both sequential and non-sequential navigation. The text includes links that provide access to a glossary, biographies of notable scientists and inventors, and related articles. Students can move through the material at their own pace and utilize links to external material as desired. To insure students are engaging in reading the material includes interactive activities to test students' comprehension such as periodic, pop-up concept questions. Students are asked to answer questions while they are reading the course material and then are given an opportunity to verify their answers. An example below concerns with the tradeoff between the pressure ratio at which gas turbine operates and the size of the engine. After students learned that the efficiency of the gas turbine engine increases with the increase of the pressure ratio they are asked to answer the following question:

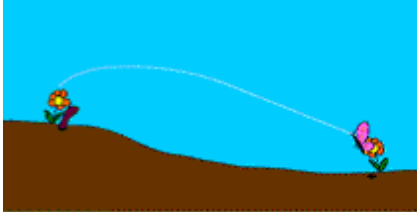
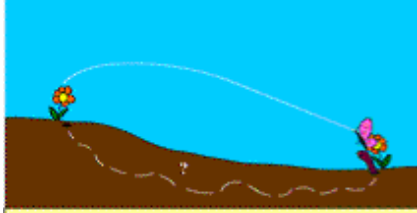
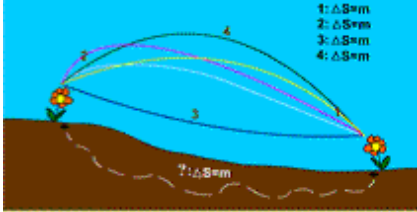
Q2: Another important factor for an engine performance is net work output. Why? Think about it and then [click here](#).

Initially the answer is hidden, so the student has an opportunity to formulate a response. If the student does not try to answer the question but only reads the answer, at least he/she knows that this is an important concept and try to understand the answer presented.

2. **Animated demonstrations** are used to help students form a mental model of a concept or process. These demonstrations are far more powerful than verbal descriptions or text accounts only. The following example shows how a concrete analogy can help clarify the challenging concept of entropy calculation for an irreversible process.

The entropy change between two specified states is the same no matter what path, reversible or irreversible, is followed during a process (see movie below).

	<p>The graph shows the change in entropy for a reversible and irreversible process. Notice that the change in entropy for each process is the same $\Delta S=0.45$ kJ/K. Only endpoint states define the change in entropy for the system no matter what path reversible or irreversible is followed during a process. Therefore we can calculate the change in entropy for irreversible process using reversible path between the specified states. The following movie uses a very simple analogy to help you understand these principles.</p>
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 <p>Note that the entire path of the process is visible. You can carry out the integration along this path and calculate the entropy at any point along the way. However, for most systems the changes between states occur irreversibly (with loss of energy for friction, dissipation, etc.) and the path for such process is not known. The worm will represent the irreversible process here.</p>	<p>Notice that the entire path of the reversible process is visible. You can carry out the integration along this path and calculate the entropy at any point along the way. However, for most systems the changes between states occur irreversibly (with loss of energy for friction, dissipation, etc.) and the path for such process is not known. The worm will represent the irreversible process here.</p>
 <p>The beginning and end points of the irreversible process are known, but the entropy at the points in between cannot be calculated. So, how can a change in entropy be calculated for an irreversible process?</p>	<p>The beginning and end points of the irreversible process are known, but the entropy at the points in between cannot be calculated. So, how can a change in entropy be calculated for an irreversible process?</p>
 <p>Although the specific system changes are different in each case, the total change in entropy is identical. This means that the change in entropy can be calculated using only the endpoints. Therefore, the change in entropy can be calculated for irreversible processes.</p>	<p>Although the specific system changes are different in each case, the total change in entropy is identical. This means that the change in entropy can be calculated using only the endpoints. Therefore, the change in entropy can be calculated for the irreversible processes.</p>

3. Interactive Exercises give students hands-on experience with some of the concepts presented in a textbook, and can even help students develop skill working with properties tables and charts. Here are only few examples of the numerous interactive exercises that are presented in the Learning Tools.

a) The following exercise focuses on an important task of defining the properties of the substance at given state using thermodynamic tables. The students are asked to fill out the table shown below:

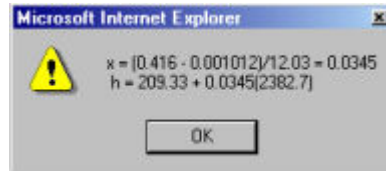
Table #1 (H₂O)

T, °C	P, kPa	v, m ³ /kg	h, kJ/kg	Phase Description
50	<input type="text"/> <input type="checkbox"/> check	0.416	<input type="text"/> <input type="checkbox"/> check hint	-select one- <input type="checkbox"/> check -select one-
<input type="text"/> <input type="checkbox"/> check	200	<input type="text"/> <input type="checkbox"/> check	<input type="text"/> <input type="checkbox"/> check	Compressed Liquid Saturated Mixture Saturated Vapor Superheated Vapor
250	400	<input type="text"/> <input type="checkbox"/> check	<input type="text"/> <input type="checkbox"/> check	-select one- <input type="checkbox"/> check
110	600	<input type="text"/> <input type="checkbox"/> check	<input type="text"/> <input type="checkbox"/> check	-select one- <input type="checkbox"/> check

Check All Answers

Reset Close

Two properties are provided for each state and the rest are left blank. There are four options under the “Phase Description” for the students to choose from (see table above). Students must determine, depending upon the phase in which substance exist, whether the saturation or superheated tables should be used and then calculate the required information. For cases that might be challenging for the beginners, such as calculation of quality of the mixture and then using the obtained quality value to calculate other characteristics of the substance, students are provided with hints. The following hint relates to the enthalpy calculation in the first row of the table above



Through the interactive table, students can receive immediate feedback, and can enter and check as many answers as necessary for each field. Answers can be checked one at a time or altogether after all fields are filled out. As a conclusion of this exercise, students are asked to fill out similar (non-interactive) tables and submit them for grading. They are provided with expert feedback from the instructor with explanations of any calculation errors. By allowing the student to work independently with a reliable error check before submitting the final table for grading, it is hoped that students will be able to work through many and correct many errors on their own. This is a very effective way to help students engage in their own learning and should greatly reduce the amount of time spent on this topic in the traditional classroom.

b) Isentropic Process Exercise helps students explore the important and complicated concept of isentropic processes and their applications to the real engineering devices. Before discussing how the mechanical (isentropic) efficiencies of the turbine and compressor account for deviation of actual compressor and turbine behavior from idealized isentropic behavior students are asked to work on the following exercise:

Choose the T-s diagram below that best represents an **actual adiabatic expansion process**:

The interface displays four T-s diagrams in a 2x2 grid. Each diagram has a vertical temperature axis (T) and a horizontal entropy axis (S). State 1 and State 2 are marked with red dots. Below each diagram is a 'Choose' button. A yellow warning dialog box from Microsoft Internet Explorer is overlaid on the top-right diagram, with the text: 'No, it is impossible for entropy to decrease during an adiabatic process. Try again.' Below the grid is a 'Continue...' link.

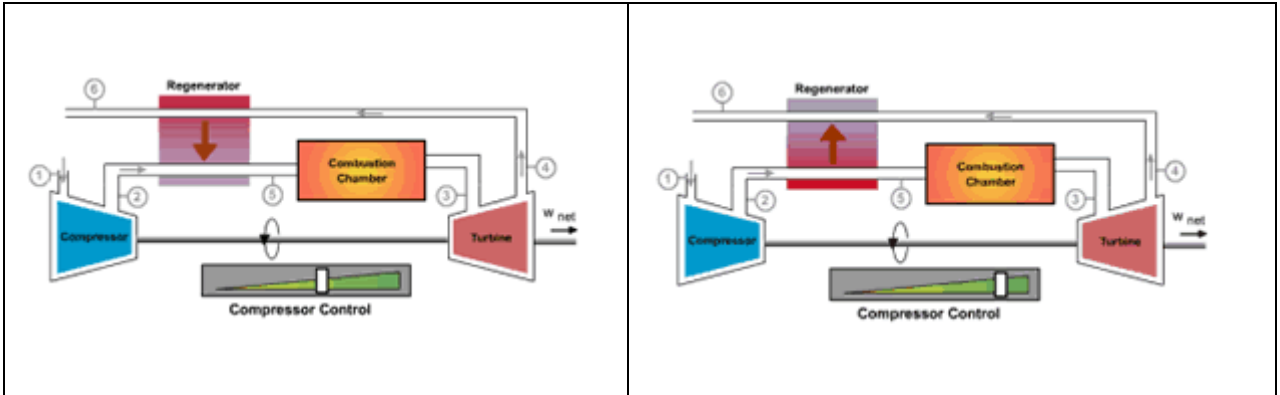
This phase of the exercise encourages students to relate their knowledge of the process to a visualization of how the process works in terms of a T-s diagram. As with the interactive table, feedback is immediate, and the student may choose more than one answer. In this exercise, the feedback for incorrect answers provides information about why the choice was incorrect. Similarly, students work with an actual adiabatic compression process.

After students complete this exercise they are introduced to the definition of the isentropic efficiency for the compressor and the turbine, they are given examples of calculations of the isentropic efficiency and asked to perform calculations themselves. These activities are designed to help students make a connection between the theoretical concepts of entropy and isentropic processes and applications in the real engineering world.

c) Another type of interactive exercises allows the students to experiment with different parameters of a system or process and see the results. An example of this type of interactive component is used to illustrate the regenerative Brayton cycle.

Why do you think the regeneration is more efficient at low pressure ratios? Think about it and [click here](#).

The students are given an opportunity to analyze this situation and make their conclusions by using an interactive animation presented below.



Use the Compressor Control to change the pressure ratio $r_p = P_2/P_1$ and see what happens

The difference between the temperature of exhausted gases T_4 and the temperature of the compressed gases leaving the compressor T_2 facilitates heat transfer through the regenerator, which in turn, increases the efficiency of the gas turbine.


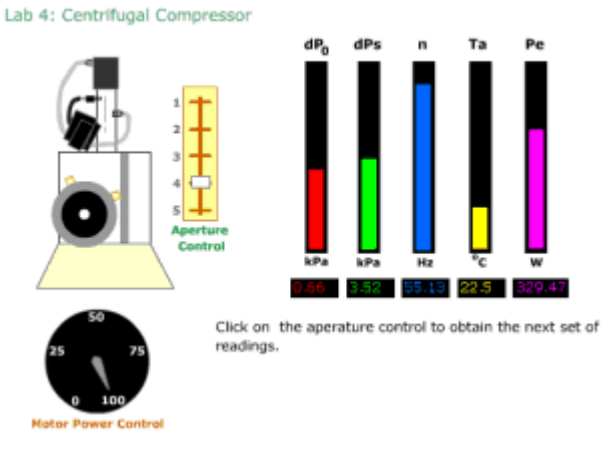
As the temperature T_2 increases with the pressure ratio $r_p = P_2/P_1 = (T_2/T_1)^{k/(k-1)}$ the difference $T_2 - T_4$ decreases (assuming T_4 does not change), which means that the less amount of heat energy can be transferred to the air in the regenerator and regenerator becomes less efficient. At some point at a high pressure ratio the temperature T_2 may become lower than T_4 and the heat energy will flow in a reversed direction to the exhaust gases decreasing an efficiency of the cycle.

4. Lab simulations are used as a culminating activity that helps students to develop skills in the higher levels of learning in the Bloom's taxonomy: Analysis, Synthesis and Evaluation. The lab simulations have been designed with sound pedagogical goals in mind. The simulation portion of the Learning Tool is well integrated into other learning activities, and the simulations as authentic and interactive as possible⁶. The following example involves experiments with the 7-stage Armfield Centrifugal Compressor, model FM 12. It is a small-scale radial flow rotodynamic machine that is available in our Thermal/Fluid Science laboratory and is normally used in the thermodynamics course for laboratory experiments.

Appropriate sensors are incorporated on the unit to facilitate analysis of the compressor performance when connected to a microcomputer. The flow of air through the compressor is regulated by a flow throttle control device installed at the exit of the discharge duct. Rotation of the collar opens and closes a variable aperture which allows the head/flow produced by the compressor to be varied.

The simulator below was created to give students an opportunity to perform experiments, to understand how the equipment works, to collect and analyze data, to make necessary calculations before they perform actual experiment in the laboratory, and, finally, as a

stimulus for the creation their own experiment. Together with the simulator students are provided with an Excel data table that they need to launch/download to record the obtained data.

	<p>Lab 4: Centrifugal Compressor</p> 
<p>7-stage Armfield Centrifugal Compressor, model FM 12</p>	<p>Compressor simulator with the computer screen.</p>

The simulator above in the position when power control corresponds to 100% of the total power, aperture control is moved to the fourth position which corresponds to the slightly open discharged duct. Next to the compressor the multicolored columns reflect the computer screen that shows five measurements corresponding to:

- Differential pressure developed across the orifice plate installed at the entrance of the inlet duct that is used to calculate the volume flow rate of air through the compressor (dP_0);
- Differential pressure developed by the compressor (dP_s);
- Rotational speed of the compressor impellers (n);
- The temperature of the air entering the centrifugal compressor (T_a);
- The electrical power supplied to the motor (P_e).

Students can perform experiments by setting the compressor at the 75%, 50%, etc., of the max speed and adjusting the compressor flow rate by using 5 positions of the aperture control.

Before the lab is performed in class, simulation experiment is assigned. The computer simulation utilizes a randomization algorithm for generating data within specified error ranges for each value collected, so each student works with a distinct set of data values and can perform the experiment more than once. This ensures that each student knows the equipment, the procedure, and the calculation routine before they come to the

laboratory to perform an actual experiment with their team. The computer simulations could also be effective for distance learning students who cannot visit the actual lab.

With the simulator described above the variety of experiments might be performed and variety of data could be analyzed. These are the characteristic curves of the Centrifugal Compressor, analyze interrelation of flow capacity, total pressure, power input, and efficiency for the Centrifugal Compressor, calculate mechanical efficiency of the compressor at different settings, calculate polytropic exponent for the compression process and finally create their own laboratory exercise using the Centrifugal Compressor.

Conclusion

The Learning Tools for undergraduate thermodynamics have been designed to meet a need for supplementary course materials to help students with difficult concepts. What is unique about these tools is that they use technology effectively in new ways and to allow learners to interact with and become engaged with the materials.

Prototype versions of some components have been tested in two sections of undergraduate thermodynamics in Fall 2003, and the results have been very positive. In course evaluations, students express their interest and approval of this novel way to learn. In discussions with the instructor, students have also communicated that interactive tables and demonstrations help them with their homework; students have expressed that concept questions help in preparation for tests. Especially positive experience was shown with laboratory experiment proposals: students made real efforts to create new experiments. Several students were willing to spend their own time after finishing the course to implement their ideas.

One of the best examples of students' lab experiments is the "diffuser experiment" proposed by Jonathan Brammell. Jonathan took Thermodynamics class in the Fall 2003 and participated in the Centrifugal Compressor lab simulation and in-class laboratory exercise. During the current semester (Spring 2004), as a part of co-op experience, he is working for the Auburndale Company in Toledo, Ohio. Jonathan spends one evening a week in our Thermal/Fluid Science laboratory working on his "diffuser experiment". The goal of the project is to modify the Centrifugal Compressor apparatus to include a study of flow through diffusers. Jonathan's original plan was to make a set of diffusers that are interchangeable with the discharged duct of the Centrifugal Compressor, but after working on the project, he has come up with a better idea. He has constructed a diffuser from an unevenly rolled heater duct held by hose clamps in a way that the cross-sectional area gradually increases from the inlet to outlet. By changing diameters of the hose clamps, the cross-sectional area of the duct can be changed at the inlet, outlet, and anywhere in between, creating a set of diffusers in one duct. Using this duct and sensors incorporated in the Centrifugal Compressor unit, the pressure and temperature of the flow through the diffusers can be measured. The objectives of proposed laboratory experiments are a) to study how the pressure and temperature change as the flow in the diffuser decelerates and b) to compare the obtained results with the pressure and temperature behavior in the accelerated flow created by varying the aperture of the exit of

the compressor's discharged duct. Jonathan Brammell's extension of the Centrifugal Compressor experiment demonstrates anecdotally how powerful the Learning Tool model and components can be in engaging students and helping them to take an active role in the learning process.

Learning Tools will be used in the Spring 2004 in two sections of undergraduate thermodynamics.

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Biographical Information

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