A walk through the synchrotron pop-up book

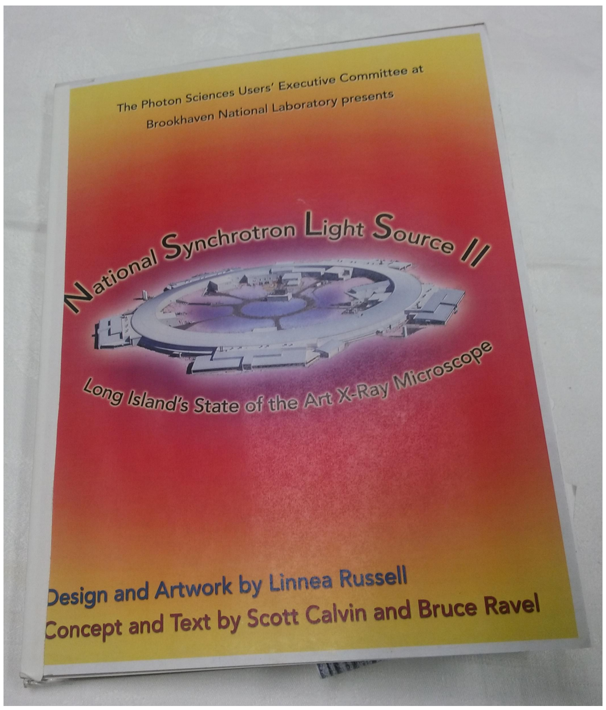
Title: National Synchrotron Light Source II

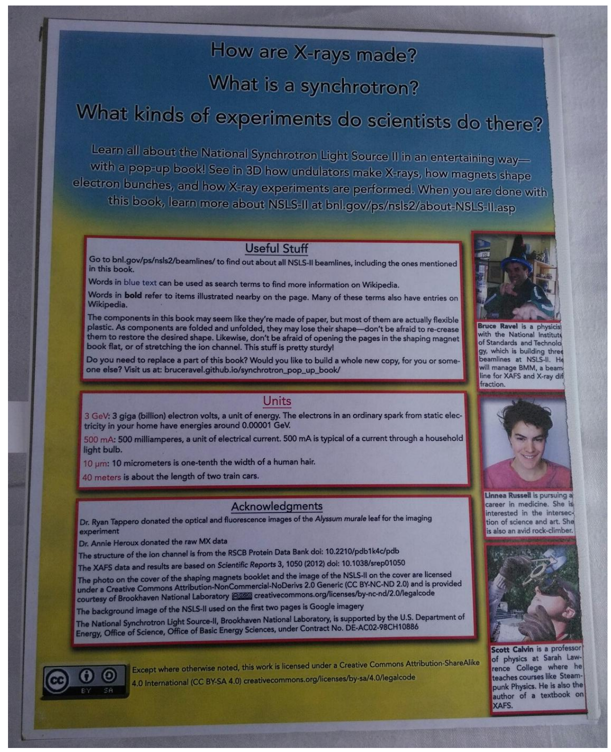
Subtitle: Long Island's Stat of the Art X-Ray Microscope

Design and Artwork: Linnea Russel

Concept and Text: Scott Calvin and Bruce Ravel

Produced by: The Photo Sciences Users' Executive Committee at Brookhaven National Laboratory

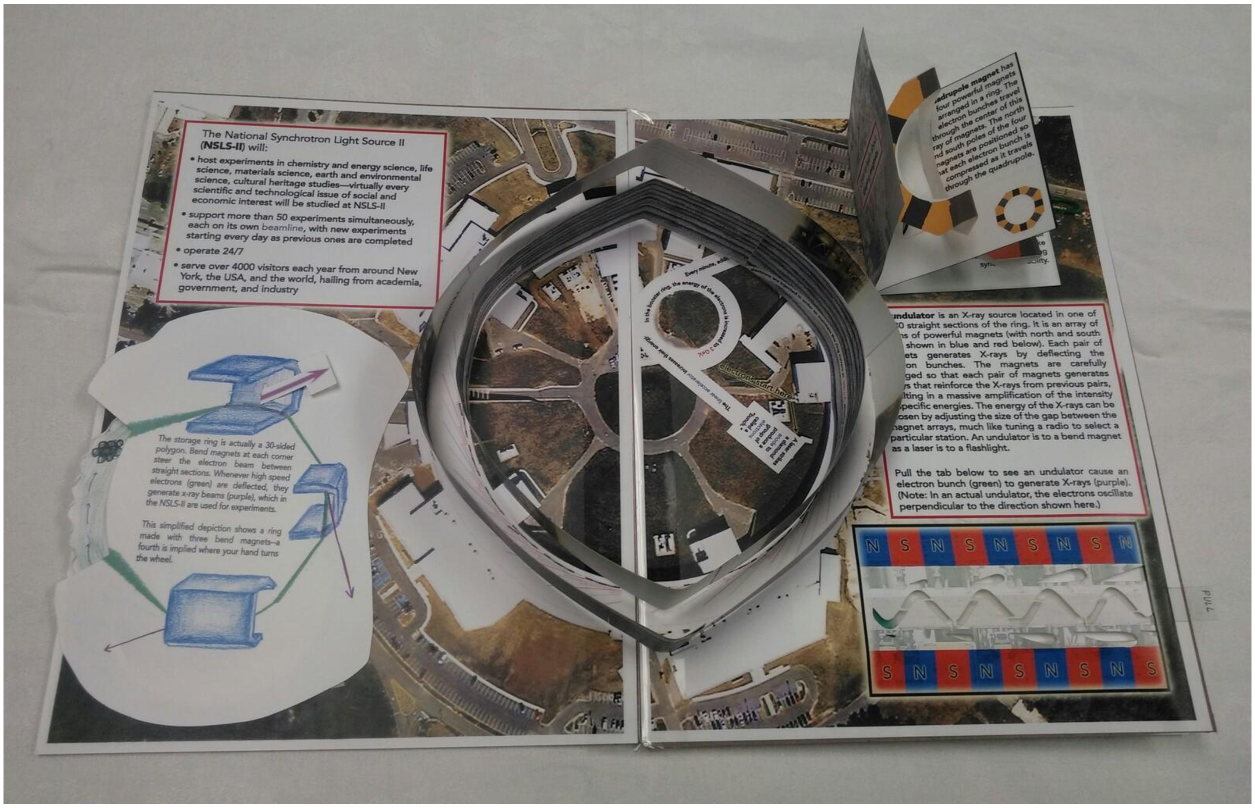




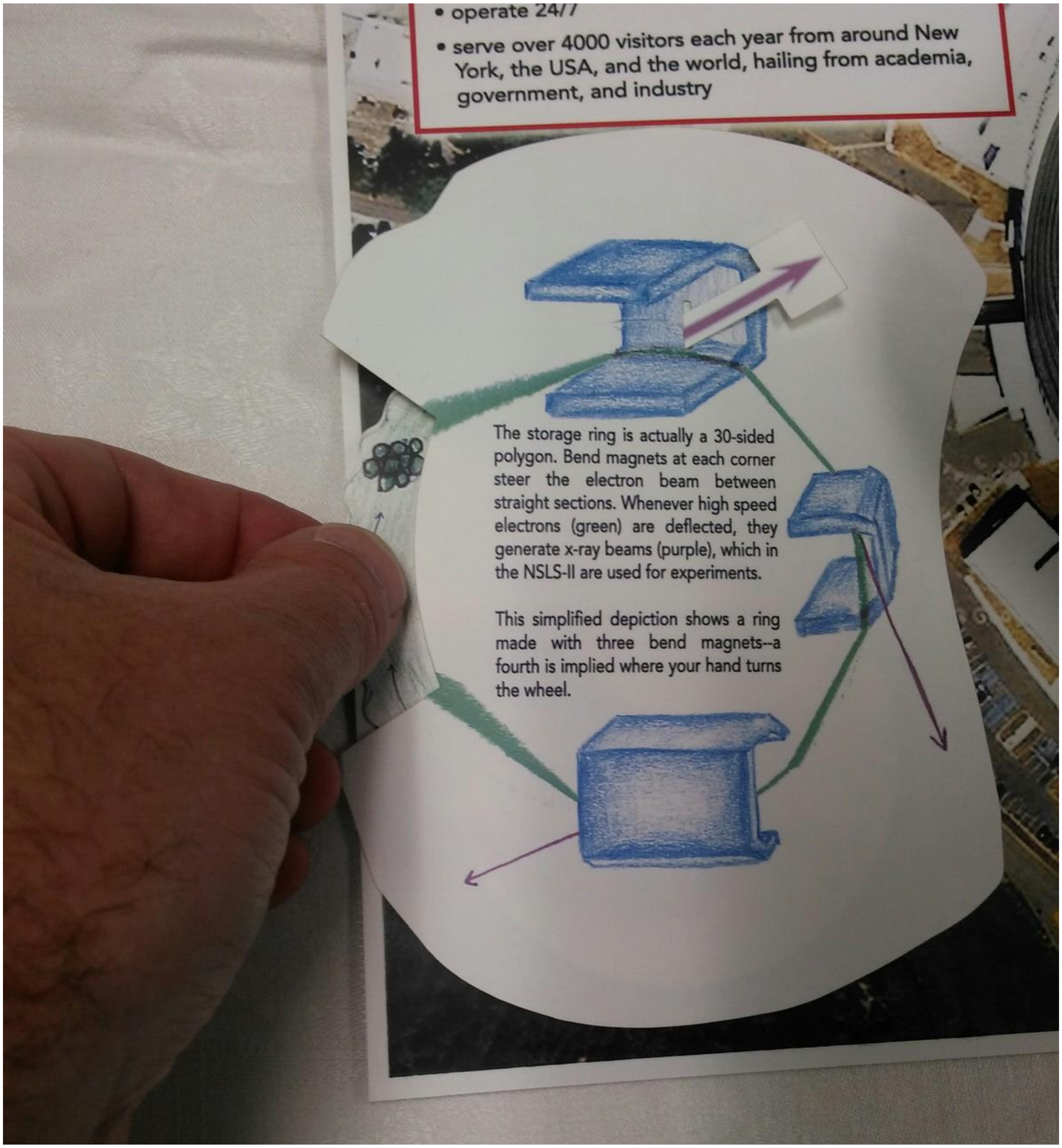
A pop-up book is meant to be played with. This walkthrough only gives a sense of what the book is and how fun it is for the reader.

1 Ring spread

The first spread depicts the NSLS-II synchrotron building.

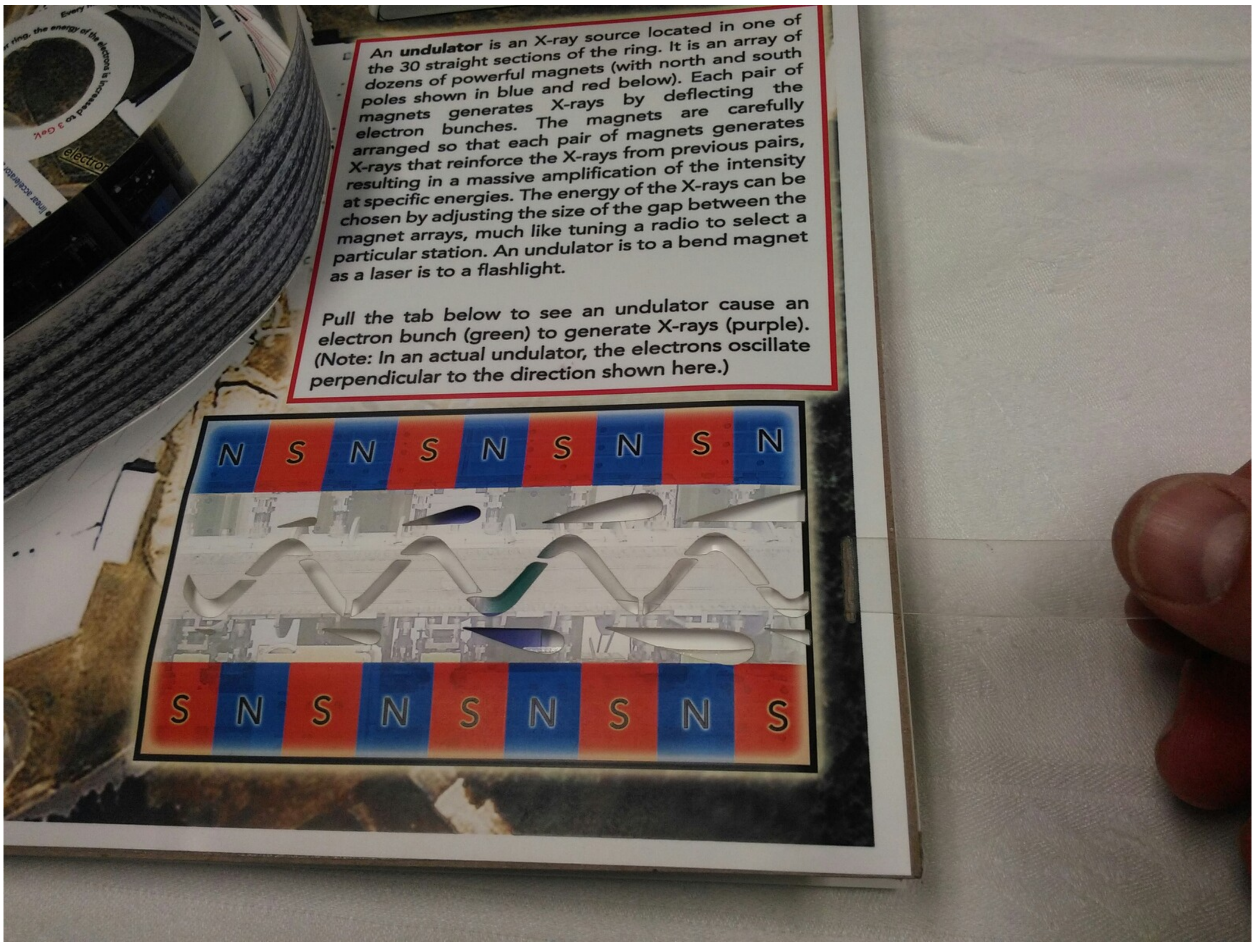


The first thing you notice is the ring itself unfolding. Be sure to read the text that starts inside the ring and continues onto the interior wall of the ring. A synchrotron is an electron storage ring – this text explains where the electrons come from. In the upper left corner is some text explaining how NSLS-II will operate as a user facility..



In the lower left corner of the ring spread is a spinner which explains how X-rays are generated from the electron current passing through a bend magnet. As the green "electron bunch" is turned clockwise, the purple arrow representing the photons extends from the bend magnet.

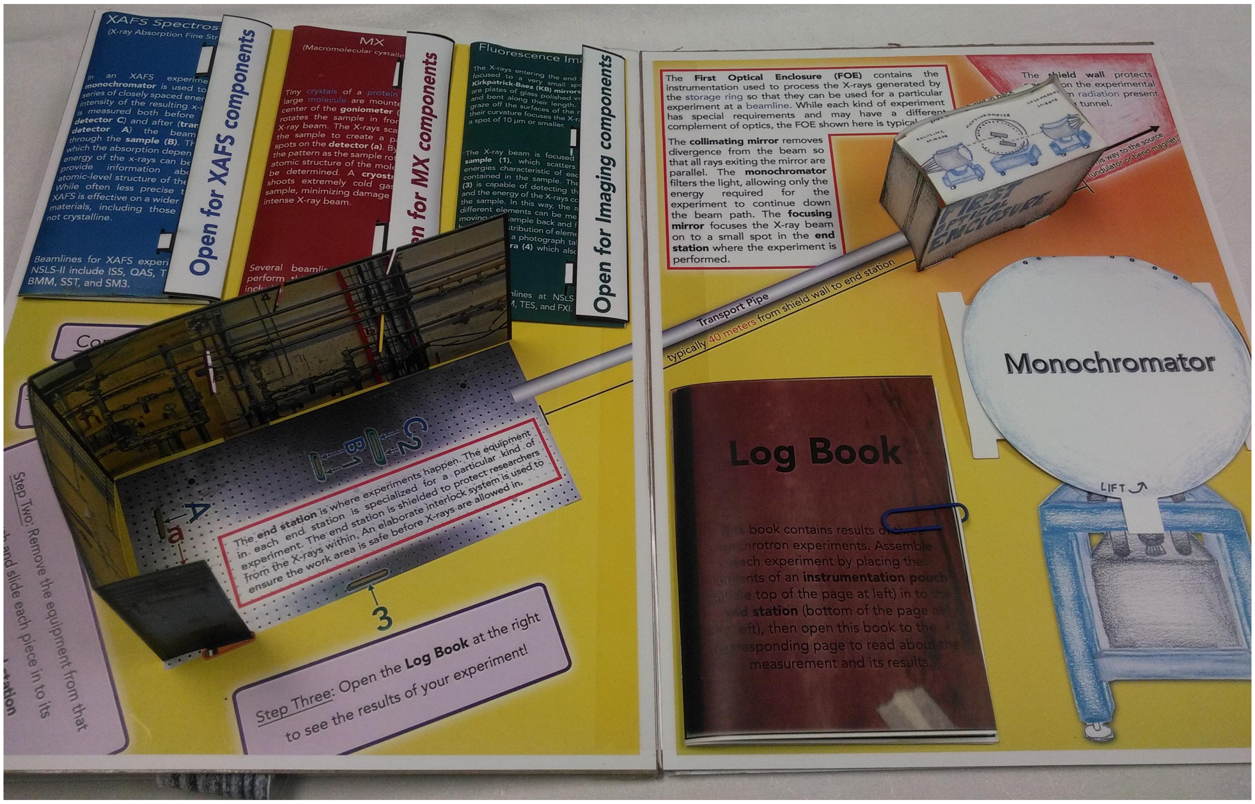
In the upper right corner is a booklet explaining how the quadrupole and sextupole magnets work to shape the electron beam, maintaining the small size required for the world-leading performance of NSLS-II.



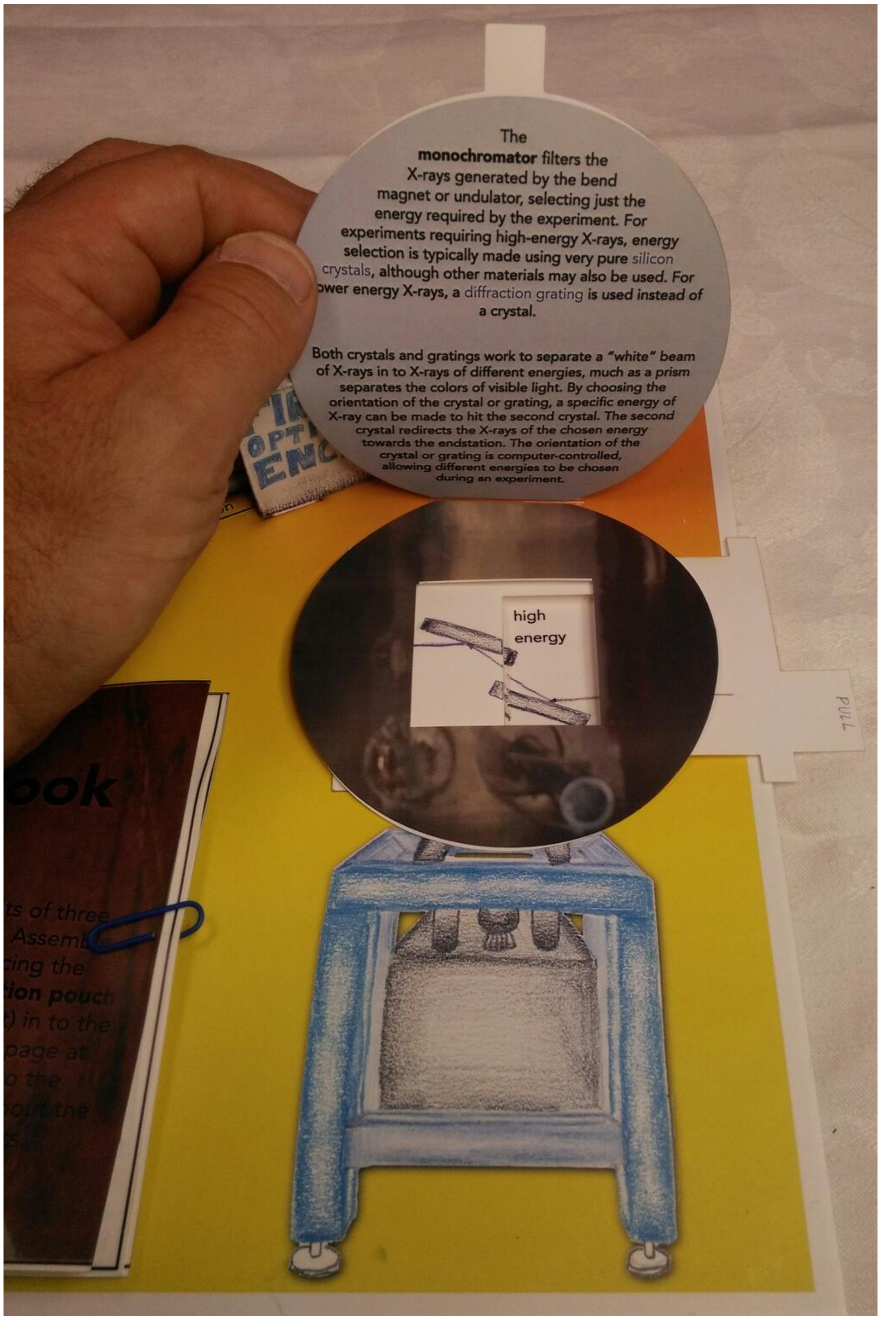
In the lower right corner is a pull tab explaining how undulators gtenerate the extremely intense, laser-like beam of X-rays that make NSLS-II a unique place to perform scientific measurements with X-rays.

2 Beamline spread

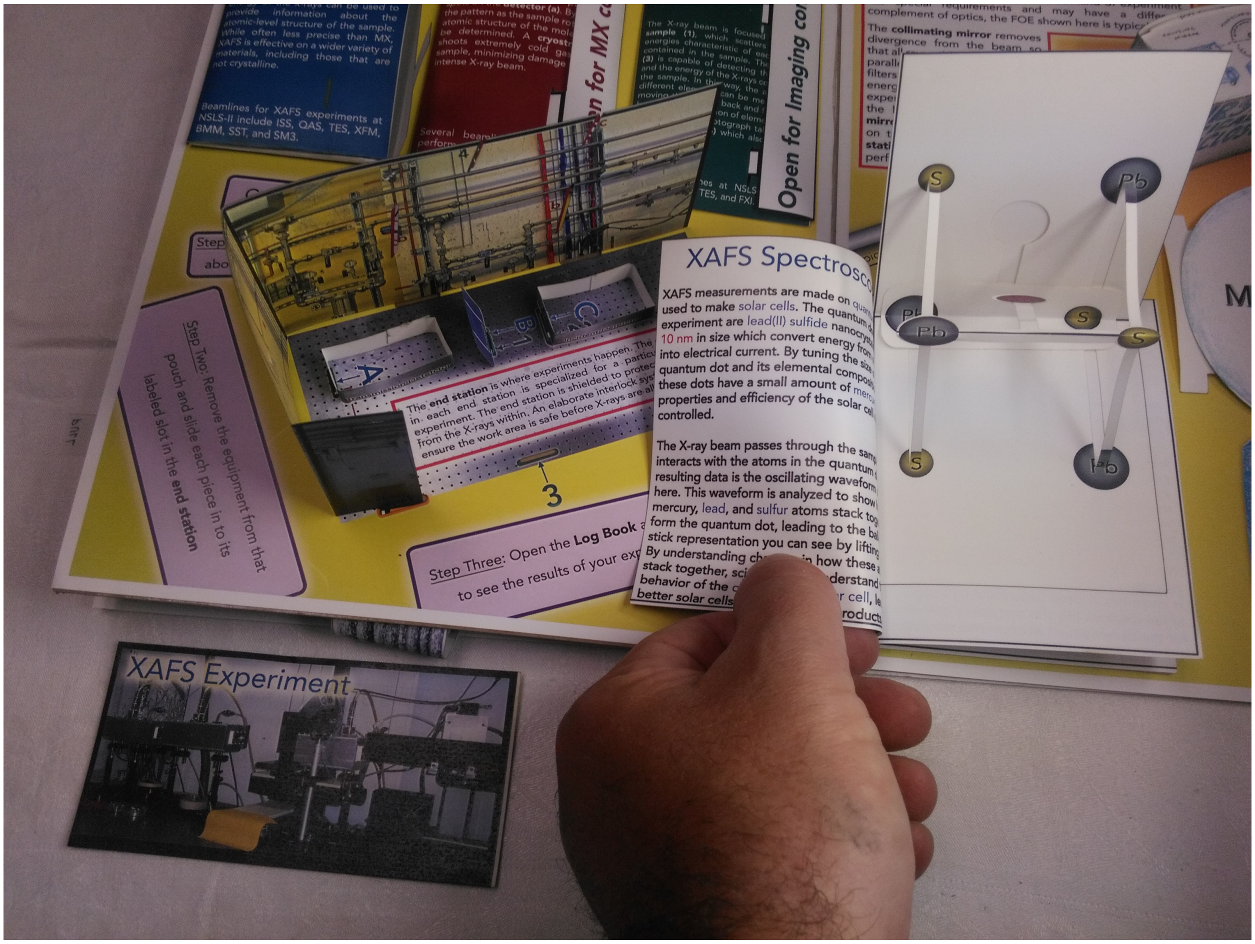
The second spread depicts a typical beamline at NSLS-II.



The three colored pouches in the upper left corner contain papercraft representations of **end station** instrumentation. You can build your own synchrotron experiment! Once you have built your experiment, open up the **log book** to the corresponding page to see an example of each of the three measurement techniques.

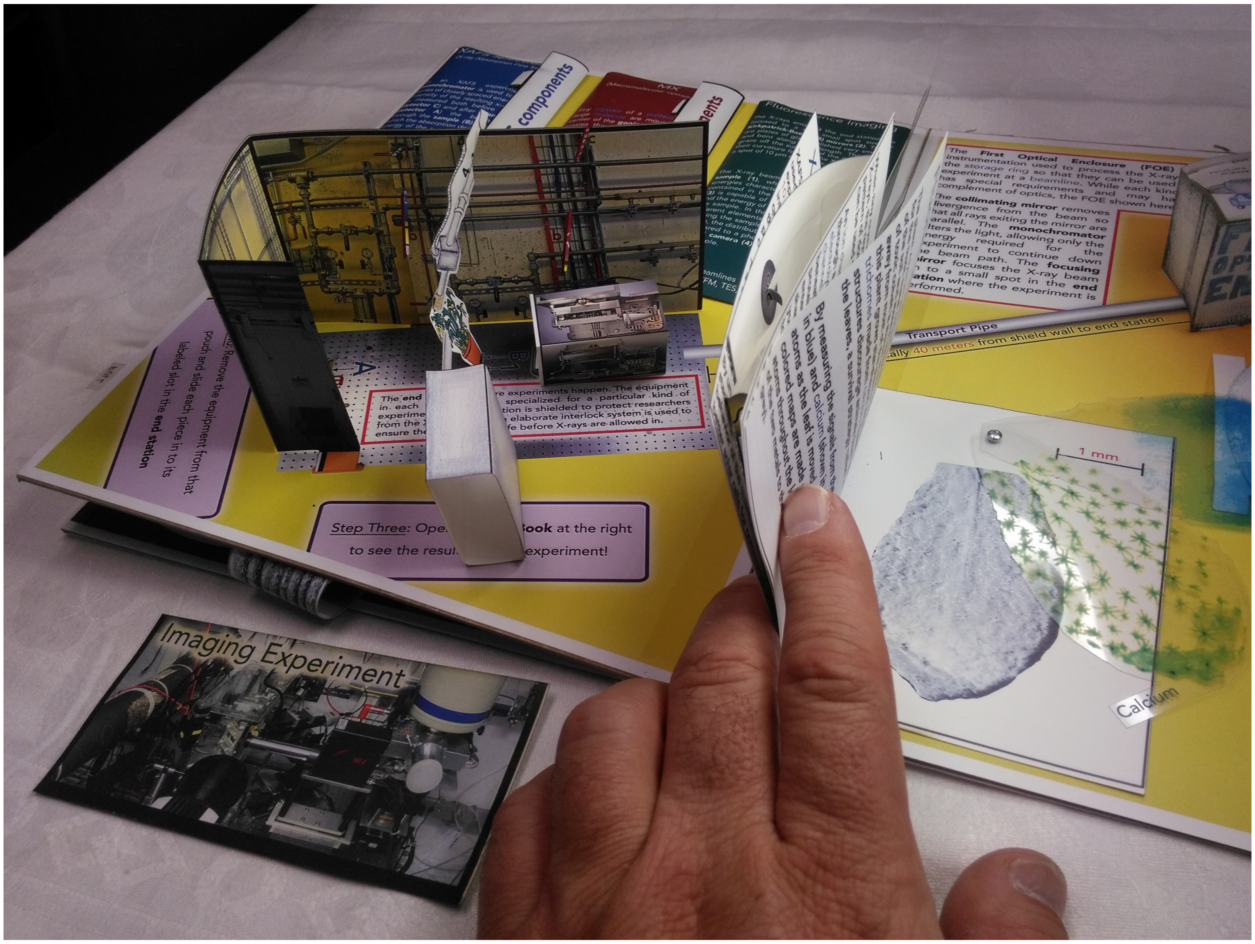


In the lower right corner is an explanation of how a monochromator is used to select the X-ray energy to be used in an X-ray measurement. Lift the cover of the monochromator to read the explanation and pull the tab to see the positions of the monochromator crystals for low and high energy X-rays.



After reading about the XAFS technique on the cover of the blue pouch, the XAFS experiment is built from the two ionization chambers within the pouch with the sample placed between the two chambers. Then the results of the XAFS experiment are shown in the **Log Book** as a 3D ball-and-stick model of the crystal structure of the sample. In this case, the structure of a material used in a quantum dot photovoltaic cell.

Next, on the red pouch you can read about the technique of macromolecular crystallography (also called MX), which is used to determine the structures of large molecules, such as the potassium ion channel depicted in the **Log Book**. The goniometer is used to precisely position the sample relative to the incoming X-ray beam. X-rays are scattered off the crystalline sample in many directions. These scattered portions of the beam are measured as spots on the X-ray camera. A cryocooler blows very cold gas at the sample to keep it frozen in order to better survive exposure to the intense X-ray beam.



Finally, you can read about the fluorescence imaging technique on the green pouch. Inside the pouch are the Kirkpatrick-Baez mirrors used to focus the X-ray beam to a spot-size below 10 micrometers. The sample, the leaf of a plant in this example, is moved back and forth in the beam. Using the silicon drift detector, a map of the locations of different metal atoms in the leaf is found and compared to a photograph of the leaf measured by the optical camera. In the **Log Book**, you will find a photo of the leaf and overlays depicting the locations of the elements cobalt and calcium.

3 Full script

The following is the full script for the book.

3.1 NSLS-II Pop-Up Book

Some notes on the format of this document:

- The script is divided into 4 sections, one each for the front and back covers and one for each of the two spreads
- Subsections describe specific papercraft elements
- {Text in braces} indicates comments to the reader of this file and will be removed from the final version of the script
- Indented (`fixed-width`) text indicates instructions about the disposition of text
- (WW Text in parens) with the "WW" marker indicates a term that can be searched for successfully on Wikipedia. This text is blue.
- (UU Text in parens) with the "UU" marker indicates a unit of measure, which will be explained on the back cover. This text is red.
- (BL Text in parens) with the "BL" marker indicates a beamline at NSLS-II. In the printed materials, no special font or color is used.
- **Bold text** in a description usually refers to a nearby papercraft element.
- URLs in the printed material are written without the leading `http://`, which is included here so that proper links are created from the markdown source.
- All other text is the actual content of the book.

3.2 Front page

The Photon Sciences Users' Executive Committee at Brookhaven National Laboratory presents
Title: National Synchrotron Light Source II
Subtitle: Long Island's state-of-the-art X-ray microscope

- Design and Artwork by Linnea Russell
- Concept and Text by Scott Calvin and Bruce Ravel

3.3 First spread: Storage ring

```
The background image is a view of NSLS-II from directly
overhead.  Along with the text and papercraft elements
described below, this image will be decorated.

The roof of the synchrotron will be decorated with a simple
representation of the layout of beamlines on the floor to look
something like this:
https://secure.flickr.com/photos/brookhavenlab/8576528221/sizes/l/

The five Lab/Office Buildings have exterior color markings
around the doors and along the rooflines.  Below is a table of
their approximate colors.  The LOBs in the image will be
decorated accordingly.

LOB | degrees | color  | R   | G   | B   | hex    |
--- | ------- | ------ | --- | --- | --- | ------ |
```

```
1    | 0        | red    | 163 | 50   | 61   | A3323D |
2    | 72       | blue   | 44  | 85   | 130 | 2C5582 |
3    | 144      | yellow | 212 | 180 | 111 | D4B46F |
4    | 216      | green  | 93  | 106 | 97   | 5D6A61 |
5    | 288      | orange | 183 | 99   | 63   | B7633F |
```

3.3.1 Overview

```
Upper left corner of this spread
```

The National Synchrotron Light Source II (**NSLS-II**) will:

- host experiments in chemistry and energy science, life science, materials science, earth and environmental science, cultural heritage studies – virtually every scientific and technological issue of social and economic interest will be studied at NSLS-II
- support more than 50 experiments simultaneously, each on its own (WW beamline), with new experiments starting every day as previous ones are completed
- operate 24/7
- serve over 4000 visitors each year from around New York, the USA, and the world, hailing from academia, government, and industry

3.3.2 Life of the electron bunches

```
This text is intended to follow a path on the page.  The
infield of the ring will depict, slightly above scale, the
linac and booster ring.  The path of text will wend its way
down the linac, all the way around the booster, down the
injection line, then around the storage ring.
```

A laser strikes a diamond (WW anode) to produce a group of (WW electrons) called a "bunch."
The (WW linear accelerator) increases their energy.
In the booster ring, the energy of the bunches is increased to (UU 3 GeV).
Every minute, additional electrons are injected in order to maintain the ring current at (UU 500 mA), allowing continuous operation for days. The stored electrons circle the (WW storage ring), traveling very close to the speed of light. As the electrons pass through bend magents and undulators, (WW X-rays) are created and delivered simultaneously to all the beamlines at NSLS-II.

3.3.3 Bend magnet

```
The papercraft depiction of a bend magnet is in the lower left
corner of this spread.  A photo of an NSLS-II bend magnet will
be printed near the papercraft.
```

The storage ring is actually a 30-sided polygon. Bend magnets at each corner steer the electron beam between straight sections. Whenever high-speed electrons (green) are deflected, they generate X-ray beams (purple) which in the NSLS-II are used for experiments.

This simplified depiction shows a ring made with three bend magnets – a fourth is implied where your hand turns the wheel.

3.3.4 Undulator

```
The papercraft depiction of an undulator is in the lower right
corner of this spread.  A photo of an NSLS-II undulator will
be printed near the papercraft.
```

An **undulator** is an X-ray source located in one of the 30 straight sections of the ring. It is an array of dozens of powerful magnets (with north and south poles shown in blue and red below). Each pair of magnets generates X-rays by deflecting the electron bunches. The magnets are carefully arranged so that each pair of magnets generates X-rays that reinforce the X-rays from previous pairs, resulting in a massive amplification of the intensity at specific energies. The energy of the X-rays can be chosen by adjusting the size of the gap between the magnet arrays, much like tuning a radio to select a particular station. An undulator is to a bend magnet as a laser is to a flashlight.

Pull the tab below to see an undulator cause an electron bunch (green) to generate X-rays (purple). (Note: In an actual undulator, the electrons oscillate perpendicular to the direction shown here.)

3.3.5 Shaping magnets booklet

```
A booklet -- i.e. a two spread book with a stiff top cover and
bound with tape -- is in the upper right corner of this
spread.  Opening the booklet to its first spread displays the
papercraft of a quadrupole magnet.  Opening the second spread
displays the papercraft of the sextupole magnet.  A photo of a
magnet girder will be printed near the booklet.

This will be cropped from this photo:
https://secure.flickr.com/photos/brookhavenlab/5589166111/sizes/l/
```

As the electron bunches travel around the storage ring, the negatively charged particles repel one another, increasing the size of each bunch. To maintain the small bunches required for proper operation of the undulators, arrays of shaping magnets are placed around the ring.

A **quadrupole magnet** has four powerful magnets arranged in a ring. The electron bunches travel through the center of this array of magnets. The north and south poles of the four magnets are positioned so that each electron bunch is compressed as it travels through the quadrupole.

A quadrupole magnet by itself has a problem. The electrons in a bunch are not all of the same energy. Electrons with slightly more energy interact with the quadrupole differently than the ones that have slightly less energy. This has the effect of stretching the length of the bunch in the direction of travel, which is bad for the operation of the undulators.

To correct this problem, every quadrupole is paired with a **sextupole magnet**. A sextupole is an arrangement of six magnets in a ring. Again, the bunches travel through the center of the sextupole array and the problem introduced by the quadrupole magnet gets corrected. Together these two kinds of magnets, repeated dozens of times around the ring, serve to maintain the ultra small bunch size required to make NSLS-II a world-leading synchrotron facility.

3.4 Second spread: Beamline

3.4.1 Shield wall

```
The colored area in the top right corner of the right page
represents the shield wall.  The transport pipe printed on the
page extends from the shieled wall to the FOE.

Text on the shield wall with an arrow pointing back toward the
source.
```

The shield wall protects people on the experimental floor from radiation present in the ring tunnel.

```
Text underneath the arrow
```

This way to the source (undulator or bend magnet)

3.4.2 First optical enclosure (FOE)

```
Near the top of the right page

The papercraft is a box that unfolds and stands upright.
"First optical encolsure" is printed on the side.  A cartoon
of the mirrors and mono is printed on the top of the box.

A tube labeled "Transport pipe" and printed on the page
connects the FOE to the end station.
```

The **First Optical Enclosure (FOE)** contains the instrumentation used to process the X-rays generated by the (WW storage ring) so that they can be used for a particular experiment at a (WW beamline). While each kind of experiment has special requirements and may have a different complement of optics, the FOE shown here is typical.

The **collimating mirror** removes divergence from the beam so that all rays exiting that mirror are parallel. The **monochromator** filters the light, allowing only the energy required for the experiment to continue down the beam path. The **focusing mirror** focuses the X-ray beam on to a small spot in the **end station** where the experiment is performed.

```
Beneath the transport pipe is a scale bar showing the distance
from the shield wall to the end station.  It is labeled with:
```

typically 40 meters from shield wall to end station

3.4.3 Monochromator

```
The papercraft monochromator is in the lower right corner.
The front of the mono, which has artwork making look like a
mono, is a flap.  This text is printed on the flap.
```

Lift here for more information about the **monochromator**

```
Underneath the flap is the papercraft mono.  On the back side
of the flap is the following text.
```

The **monochromator** filters the X-rays generated by the bend magnet or undulator, selecting just the energy required by the experiment. For experiments requiring high-energy X-rays, energy selection is typically made using very pure (WW silicon crystals), although other materials may also be used. For lower energy X-rays, a (WW diffraction grating) is used instead of a crystal.

Both crystals and gratings work to separate a “white” beam of X-rays into X-rays of different energies, much as a prism separates the colors of visible light. By choosing the orientation of the crystal or grating, a specific energy of X-ray can be made to hit the second crystal. The second crystal redirects the X-rays of the chosen energy towards the end station. The orientation of the crystal or grating is computer-controlled, allowing different energies to be chosen during an experiment.

```
The pull tab displays the mono crystals in two orientations.
The two orientations are labeled "Low energy" and "High
energy".
```

3.4.4 End station

```
The end station occupies most of the lower half of the left
page.  The papercraft component of the end station is two
walls that unfold to stand upright.  The walls are printed
with photos of interior and exterior end station walls from
NSLS-II.

A photo of an optical table is printed on the "floor" of the
end station.  This is the surface on which the reader will
assemble the papercraft experiments.

The first four of the following paragraphs are in boxes and
scattered around the end station.  The fifth paragraph is
printed on the floor of the end station.
```

Conduct your own experiment!

Step One: Choose one of the pouches above and read about a technique.

Step Two: Remove the equipment from that pouch and slide each piece into its labeled slot in the end station.

Step Three: Open the **Log Book** at the right to see the results of your experiment!

The end station is where experiments happen. The equipment in each end station is specialized for a particular kind of experiment. It is shielded to protect researchers from the X-rays within. An elaborate interlock system is used to close the end station and make the work area safe before the X-ray shutter can be opened.

3.4.5 Instrumentation pouches

```
Above the set of pouches, in bold text:
```

Instrumentation pouches

```
Each pouch should be colored with the color assigned to its
experiment.  This color coding connects the pouch to the
individual instruments and to the pages of the data booklet.
Each item in the following list is printed on its colored
pouch.
```

- X-ray Absorption Fine Structure Spectroscopy (XAFS) (Color: blue)
- Macromolecular Crystallography (MX) (Color: maroon)
- Fluorescence Imaging (Color: green)

3.4.6 Data booklet cover

```
Lower left corner of the right page

Print the cover of the booklet to look like an experimental
log book.

This will be a booklet in the same sense as the shaping
magnets booklet on the previous spread.  It will have a
cardboard outer cover and be bound by tape.

Big, bold text
```

Log book

```
smaller text
```

This book contains results of three synchrotron experiments. Assemble each experiment by placing the contents of an **instrumentation pouch** (at the top of the page at left) in to the **end station** (bottom of the page at left), then open this book to the corresponding page to read about the measurement and its results.

```
The pages will be color coded to correspond to the experiments
```

3.4.7 Experiments

```
Each experiment requires text for the instrumentation objects
and for the presentation of results in the log book
```

X-ray Absorption Fine-Structure (XAFS) Spectroscopy

Instrumentation

```
printed on the XAFS pouch
```

In an XAFS experiment, the **monochromator** is used to select a series of closely spaced energies. The intensity of the resulting x-ray beam is measured both before (**incident detector C**) and after (**transmission detector A**) the beam passes through the **sample (B)**. The way in which the absorption depends on the energy of the X-rays can be used to provide information about the atomic-level structure of the sample. While often less precise than MX, XAFS is effective on a wider variety of materials, including those that are not crystalline.

Beamlines for spectroscopy experiments at NSLS-II include (BL ISS), (BL QAS), (BL TES), (BL XFM), (BL BMM), (BL SST), and (BL SM3).

Experiment

```
printed in the Log Book near the data
```

XAFS measurements are made on (WW quantum dots) used to make (WW solar cells). The quantum dots in this experiment are (WW lead(II) sulfide) nanocrystals about (UU 10 nm) in size which convert energy from sunlight into electrical current. By tuning the size of the quantum dot and its elemental composition – these dots have a small amount of (WW mercury) – the properties and efficiency of the solar cell are controlled.

The X-ray beam passes through the sample and interacts with the atoms in the quantum dots. The resulting data is the oscillating waveform shown here. This waveform is analyzed to show how the mercury, (WW lead), and (WW sulfur) atoms stack together to form the quantum dot, leading to the ball-and-stick representation you can see by lifting the data. By understanding changes in how these atoms stack together, scientists can understand the behavior of the (WW quantum dot solar cell), leading to better solar cells for commercial products.

Macromolecular crystallography

Instrumentation

```
Printed on the MX pouch
```

Tiny (WW crystals) of a (WW protein) or other large (WW molecule) are mounted at the center of the **goniometer (b)**, which rotates the sample in front of the X-ray beam. The X-rays scatter from the sample to create a pattern of spots on the **detector (a)**. By tracking the pattern as the sample rotates, the atomic structure of the molecule can be determined. A **cryostream (c)** shoots extremely cold gas at the sample, freezing the sample, and minimizing damage caused by the intense X-ray beam.

Several beamlines at NSLS-II will perform this kind of measurement, including (BL AMX), (BL FMX), (BL NYX), and (BL SM3).

Experiment

```
printed in the Log Book near the data
```

When tiny crystals of a protein are exposed to X-rays, the rays undergo (WW diffraction), forming a pattern of dots like the one shown at right, which can be used to determine the protein's structure.

An (WW ion channel) allows only one kind of atom to pass through a cell wall, maintaining a balance of (WW electrolytes) within the cell. The (WW potassium ion channel) (lift the diffraction pattern up and look beneath to see it) consists of four copies of a protein linked in a ring. When a potassium ion enters one end of the channel, the proteins change shape, like what happens to the paper model when you stretch it. This shape change transports the ion to the other side of the cell wall.

Work performed at NSLS (the predecessor to NSLS-II) on this protein led to the 2003 Nobel Prize in chemistry. A deep understanding of the behavior of ion channels like this one opens new prospects for the development of novel pharmaceuticals.

Fluorescence imaging

Instrumentation

```
printed on the Imaging pouch
```

The X-rays entering the end station are focused to a very small spot by **Kirkpatrick-Baez (KB) mirrors (2)**. These are plates of glass polished very smooth and bent along their length. The X-rays graze off the surfaces of the mirrors and their curvature focuses the X-ray beam to a spot of (UU 10 um) or smaller.

The X-ray beam is focused on to the **sample (1)**, which scatters X-rays at energies characteristic of each (WW element) contained in the sample. The **detector (3)** is capable of detecting the intensity and the energy of the X-rays coming from the sample. In this way, the amounts of different elements can be measured. By moving the sample back and forth in the beam, the distribution of elements can be compared to a photograph taken by the **optical camera (4)** which also points at the sample.

Imaging beamlines at NSLS-II include (BL HXN), (BL SRX), (BL XFM), (BL TES), and (BL FXI).

Experiment

```
printed in the Log Book near the data
```

The plant (WW *Alyssum*) *murale* is a (WW hyperaccumulator) for the toxic metal (WW cobalt) – it can draw cobalt out of the soil and store it within its leaves. This excess of toxic cobalt is stored at the tip of the leaf, far away from the rest of the plant's tissues. Additionally, this plant grows star-shaped structures called (WW trichomes) made from (WW calcite). These hard, mineral structures discourage animals from wanting to eat the leaves, a survival strategy called (WW antiherbivory).

By measuring the signals from the cobalt (shown in blue) and (WW calcium) (shown in yellow-green) atoms as the leaf is moved under the X-ray beam, colored maps are made of the locations of those atoms throughout the leaf. Compare the locations of the two metals to the photograph (shown in grey).

{Note that “Alyssum” is currently an entry in Wikipedia, but “Alyssum murale” is not. Also note that *Alyssum murale* must be set in *italics*.}

3.5 Back page

3.5.1 Blurb

`Top of page, fairly big font`

How are X-rays made?
What is a synchrotron?
What kinds of experiments do scientists do there?
Learn all about the National Synchrotron Light Source II in an entertaining way – with a pop-up book! See in 3D how undulators make X-rays, how magnets shape electron bunches, and how X-ray experiments are performed. When you are done with this book, learn more about NSLS-II at: http://bnl.gov/ps/nsls2/about-NSLS-II.asp

3.5.2 Biographies

`Photos of Linnea, Scott, and Bruce with short bios`

Bruce Ravel is a physicist with the National Institute of Standards and Technology, which is building three beamlines at NSLS-II. He will manage (BL BMM), a beamline for XAFS and X-ray diffraction.
Linnea Russell is pursuing a career in medicine. She is interested in the intersection of science and art. She is an avid rock climber.
Scott Calvin is a professor of physics at Sarah Lawrence College where he teaches classes like Steampunk Physics. He is also the author of a textbook on XAFS.

3.5.3 Useful Stuff

`boxed text`

- Go to http://bnl.gov/ps/nsls2/beamlines/ to find out about all NSLS-II beamlines, including the ones mentioned in this book.
- Words in (WW blue text) can be used as search terms to find more information on Wikipedia .
- Words in **bold** refer to items illustrated nearby on the page. Many of these terms also have entries on Wikipedia.
- the components of this book may seem like they’re made of paper, but most of them are actually flexible plastic. As components are folded and unfolded, they may lose their shape – don’t be afraid to re-crease them to restore the desired shape. Likewise, don’t be afraid of opening the pages in the shaping magnet book flat, or of stretching the ion channel. This stuff is pretty sturdy!
- Do you need to replace a part of this book? Would you like to build your own copy of this book? Visit us at: http://bruceravel.github.io/synchrotron_pop_up_book/

3.5.4 Units

`boxed text (or similar) with color/font link to units in text`

- 3 GeV: 3 giga (billion) electron volts, a unit of energy. The electrons in an ordinary spark from static electricity in your home have energies around 0.00001 GeV.

- 500 mA: 500 milliamperes, a unit of electrical current. 500 mA is typical of the current through a household light bulb.
- 10 um: 10 micrometers is one tenth the width of a human hair.
- 40 meters is about the length of two train cars.

3.5.5 Acknowledgments

`boxed text`

- Dr. Ryan Tappero donated the optical and flourescence images of the *Alyssum murale* leaf and for the photo of the imaging experiment
- Dr. Annie Heroux donated the raw MX data
- The structure of the ion channel is from the RSCB Protein Data Bank doi: 10.2210/pdb1k4c/pdb
- The XAFS results are from *Scientific Reports* 3, 1050 (2012) doi: 10.1038/srep01050
- The photo on the cover of the shaping magnets booklet and the image of the NSLS-II on the cover are licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 2.0 Generic (CC BY-NC-ND 2.0) license and are provided courtesy of Brookhaven National Laboratory http://creativecommons.org/licenses/by-nc-nd/2.0/legalcode
- The background image of NSLS-II used on the first two pages is Google imagery.
- The National Synchrotron Light Source-II, Brookhaven National Laboratory, is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.

3.5.6 License