X-Rays, Dartmouth and the Growth of American Physics
The Dartmouth link, 1896

- Eddie McCarthy breaks wrist, 19 Jan
- Edwin Frost, Dartmouth prof of physics & astr.
  - Learns of Röntgen’s discovery, 26 Jan
  - Makes first “shadow picture,” 1 Feb
  - Makes first “clinical x-ray” with 20-minute exposure, 3 Feb
    - Submits “Experiments in X-Rays” to Science, 4 Feb, published 14 Feb
      - Prism would not refract x-rays; no speculation about theory
      - Concludes: “Comment upon the numerous applications of the new method in the sciences and arts would be superfluous.”
  - Second Science article, 27 Feb
    - Tries to measure $\lambda$ by diffracting x-rays around edges of obstacles; attributed observed distortion to electrostatic effects
    - Explanation ridiculed in 4/24/1896 Science article
    - Frost never published again on x-rays
Task of lecture

- Who was Röntgen and how did he make his discovery?
  - An “average” physicist at end of classical era, before “genius” founders of “modern” physics like Einstein, Planck, Bohr, etc.

- Why did physicists everywhere rush to repeat Röntgen’s experiment?
  - Another laboratory problem for classical physics

- Why the popular fascination with x-rays?
  - Forbidden pleasure of “seeing inside” things
Röntgen’s life, 1845-1923

- Son of a wealthy cloth manufacturer
  - Besitzbürgertum, not Bildungsbürgertum

- Peripatetic career as academic physicist
  - Expelled from high school without diploma
  - PhD in experimental physics in Zürich, 1869
  - Average career as “experimental physicist” at 5 universities and 1 agricultural academy

- But won first Nobel Prize in physics for discovery of x-rays, 1901
A career of movement
Context of R’s discovery

- All contemporary records burned by Röntgen
- Measures very small physical effects, not related to theory (Röntgen was colorblind!)
  - Often scooped by competitors
  - 1893 speech: experiment as “purveyor of disappointment”
- But did two theory-driven experiments
  - Confirmed Maxwell’s prediction of magnetic effects if move glass in electric field - became “Röntgen current” by 1888
  - Confirmed Helmholtz’s prediction from Maxwell of a very high-frequency electromagnetic radiation that interacts minimally with matter - became “Röntgen rays” [=x-rays] by 1895
Physics of “cathode rays”

- Geissler tubes, 1850s: filled with gases
  - Produce glowing light, bright spectral lines
  - Deflected by magnets

- Cathode ray tubes, 1870s: better vacua
  - Cathode rays invisible, but fluoresce screens
  - Move in straight lines from cathode(-) to anode(+)
  - Deflected by magnets, pass through glass & air
  - Negatively charge objects they hit
  - Called “radiant matter” (4th state) by Crookes in 1876
“Discovering” x-rays

Three non-discoveries

- Crooke’s “defective” photographic plates, 1880s
- Lenard’s exposed plates covered with paper impenetrable to cathode rays, 1880s
- Goodspeed’s shadow photographs, 1890

Röntgen’s discovery and 3 papers, 1895-96

- Lucky accident, seeking Helmholtz’s ‘rays’ in darkened room with fluorescent screen
- X-rays more penetrating than cathode rays
- Saw shadow of bone in his finger on screen
Röntgen’s x-ray tube

High DC voltage

cathode

Copper anode

Cathode

Cathode rays

x-rays
Characteristics of R’s x-rays

- Travel in straight lines, not deflected by magnets
- Penetrate 2 m of air, 2 cm of wood, 1000-page book, cardboard
- Differentially absorbed by materials
- Not reflected or refracted by optical glass
- Exposed photographic plates and excited fluorescent screens
- Röntgen’s initial theory, not further elaborated
  - Lack of refraction suggests are NOT electromagnetic radiation like light, ultraviolet or infrared (i.e., transverse waves in aether)
  - Perhaps x-rays are longitudinal waves in aether (i.e., sound waves of very high pitch)?
X-rays, sensation of 1896

- Röntgen mailed preprints and photo on 1/1/96
  - Röntgen himself predicted widespread interest
- Reported in journals and newspapers
  - Experiments repeated everywhere
  - Bones in hand becomes icon of the discovery
  - Röntgen demonstrated x-rays to the German Kaiser in Berlin, Jan 1896, awarded Prussian Order
- More than 1000 articles published in 1896
  - Frost’s two articles part of a flood
Why the public interest?

- **Furthered 19c technologies of seeing**
  - Photography, stereoscope, binoculars, kaleidoscope
  - “Seeing inside” and Victorian prudishness
  - Linked to popular fads and hopes of tabloid press
    - Iron into gold, learning anatomy, spiritualism, temperance

- **Medical use begins immediately**
  - Diagnosis of broken bones, teeth, foreign objects in body
  - Anatomical information with fluoroscopy
  - Therapy for cancer, blindness, birthmarks
    - No dosage limits for first decade!
  - X-ray departments in hospitals already by 1896

- **Real-time movies of the human body**
  - Opera singing and the voice
  - Shoe stores
X-rays in physics

- Proliferation of theoretical explanations
  - High velocity cathode rays?
  - Vortex rings in the aether?
  - Small particles moving a high speed?
  - Aether wind?

- X-ray diffraction confirms electromagnetic wave theory in 1912
  - Max von Laue’s idea of crystals as space lattice that diffracts waves with $\lambda \approx d$ (Nobel Prize, 1914)
  - Bragg’s law of x-ray diffraction (Nobel Prize, 1915)
  - Explanation of x-ray production would come with Bohr model of the atom (also explained spectral lines)--next lecture!
Bragg’s law, 1912

Incoming beam

If know d, measure θ, can compute λ

Exiting beam with constructive interference

2d\sinθ = nλ

Extra path length
X-rays become physics tool

- Mosley relates $\lambda$ to element of anode
  - Predicts elements then not known to chemists
- X-rays ionize gases
- X-ray crystallography probes structure of crystalline solids (structure of DNA 1952-53)
- X-rays from astronomical objects
  - Stars, gas clouds, matter entering black holes
- Extra-scientific uses--many needs to “see inside”
  - Archaeology, manufacturing, food preservation, etc.
Physics in America to 1939

- Remained ‘natural philosophy’ until 1880s
- Student laboratory movement of 1880s
  - Driven by Harvard’s 1886 lab requirement for admission
  - Goal was to promote independent thinking, not to create research physicists
  - Stimulated instrument-making industries
- Rowland’s style of experimental physics
- Lack of standards to elevate research
  - Students lacked advanced mathematical skills
  - *Physical Review* founded at Cornell in 1893; American Physical Society founded 1899
  - Many Americans went to Europe for PhDs or postdocs
  - Private philanthropy of 1920s, New Deal of 1930s
Measuring the pressure of light, Dartmouth, 1901-3