

X-ray Imaging and MicroCT

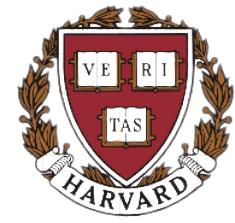
Summer Course #6

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Center for Nanoscale Systems

Harvard University

7/18/2014 Friday



X-ray Imaging and MicroCT at CNS

X-TEK HMXST225 → Now owned by Nikon Metrology



Certainly THE instrument at CNS with the most diverse group of users and samples!

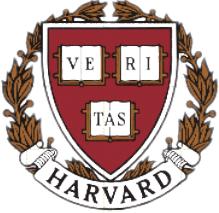


X-ray Imaging and MicroCT at CNS

A versatile and non-destructive technique for:

- 2D imaging
- 3D visualization, sectioning and comparison
- Metrology
- Quality control
- Porosity/inclusion analysis
- Defect/failure analysis
- Material density analysis
- CAD-to-prototype comparison
- Reverse engineering

At micron scale!



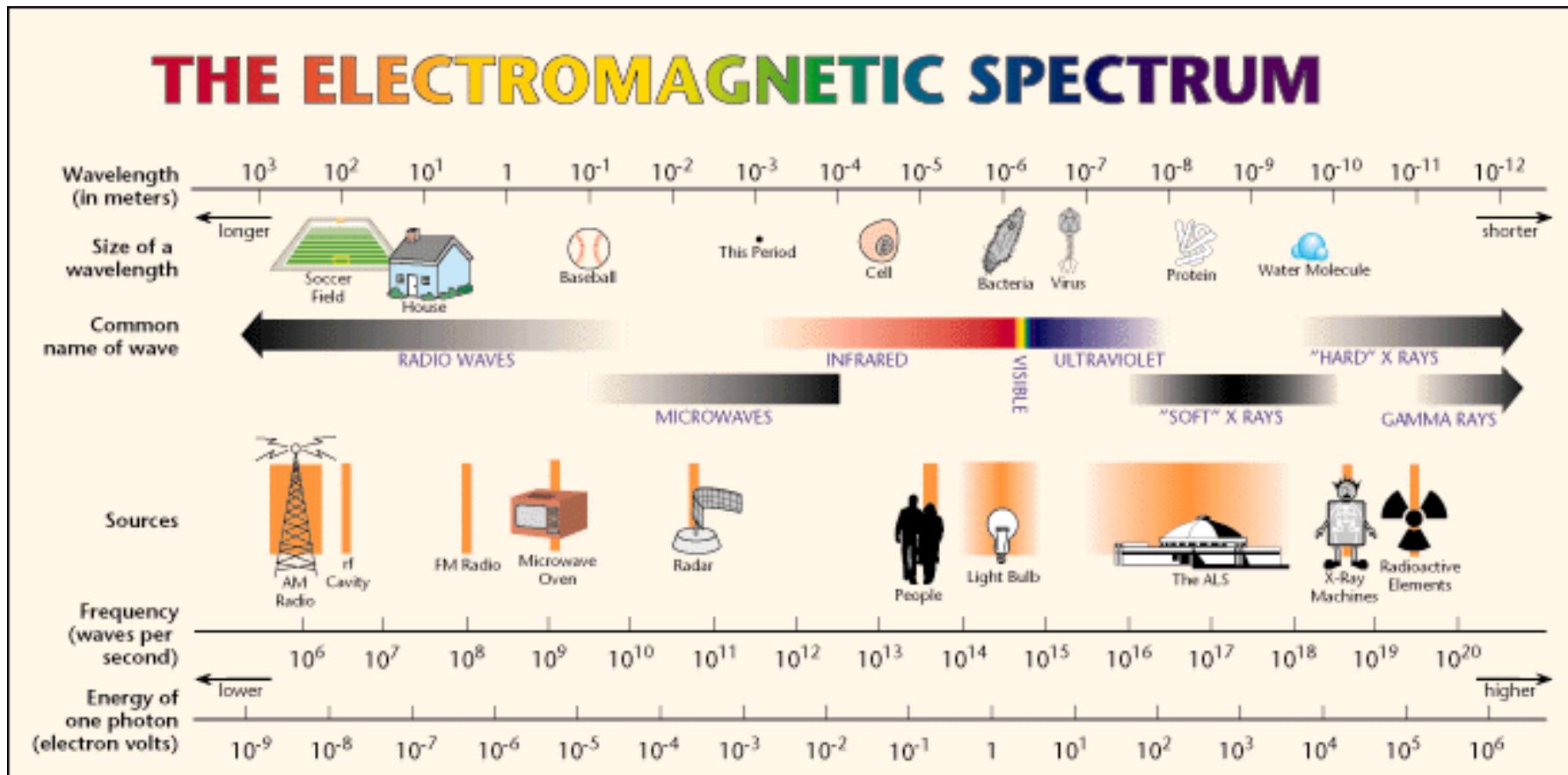
Overview

- What are X-rays, and how do we generate them?
- 2D micro-imaging using X-rays
- How does X-ray microCT work?
- How are 3D volumes reconstructed from 2D images?
- Rendering and visualizing 3D volume files
- Artifacts in X-ray microCT and how to minimize them
- Examples of X-ray imaging and microCT

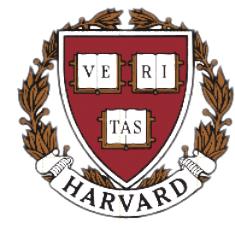


What are X-rays?

X-rays are electromagnetic radiation just like visible light, infra-red light, ultra-violet light and radio waves, but with a much shorter wavelength, hence with much higher energy, than any of these.



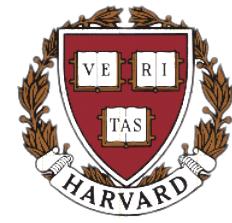
X-Tek X-ray sources produce energies in the range 30-450keV.



First X-ray Image



*The discoverer of X-rays,
Wilhelm Röntgen's first
radiograph (1895): the low
energy X-rays penetrated the
bone but not the gold ring.*

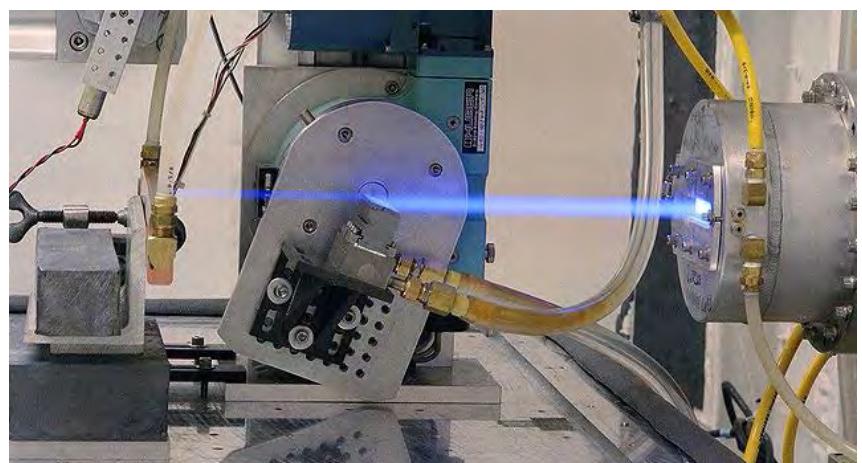
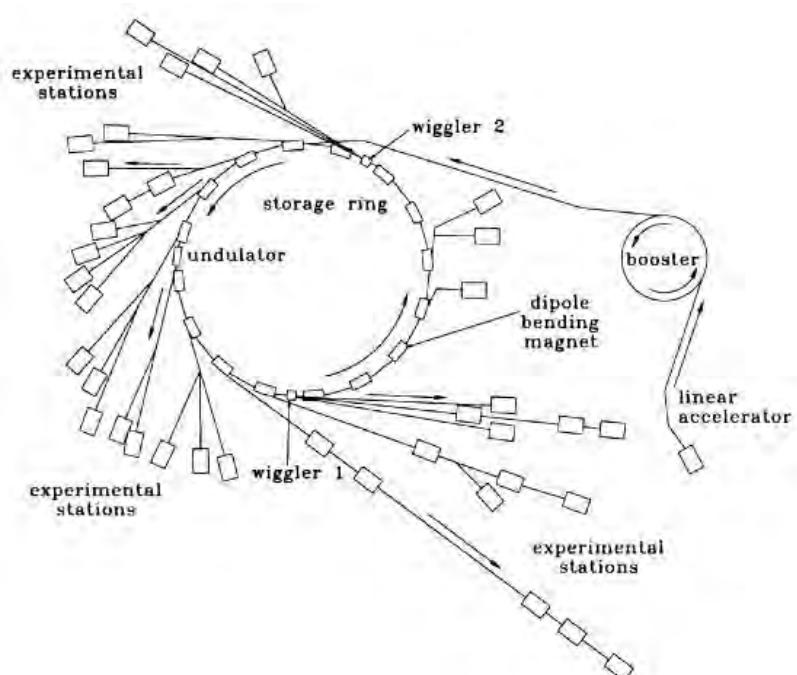


How to generate X-rays?

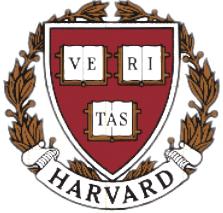
The very expensive way:

1) Synchrotron radiation

- E.g. Argonne National Laboratory
- high-energy electron beam: directed into auxiliary components (e.g. bending magnets and insertion devices) supplying strong magnetic fields perpendicular to the beam



Synchrotron radiation emerging from a beam port. The blue color comes from oxygen and nitrogen atoms in the air, ionized by the X-rays (Source: Wikipedia).

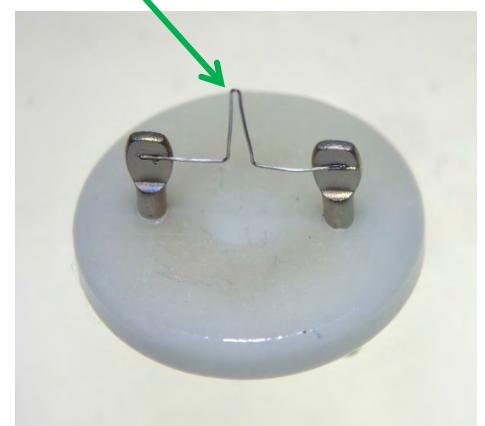
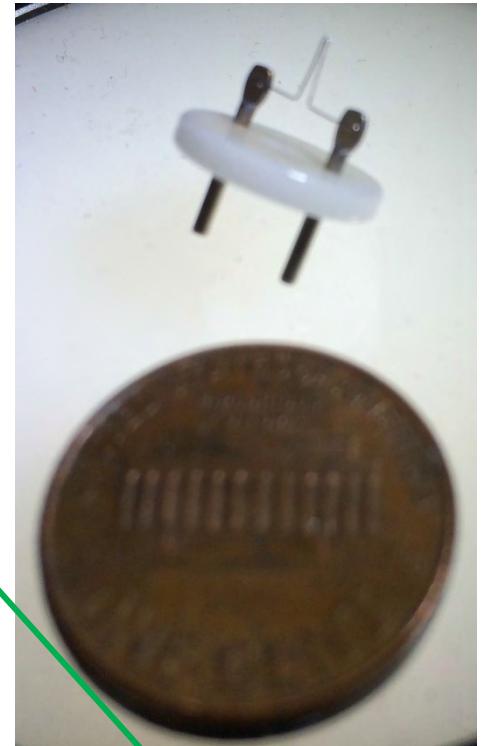


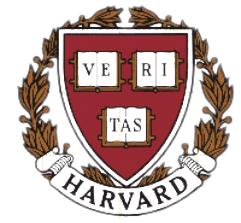
How to generate X-rays?

The much less expensive way:

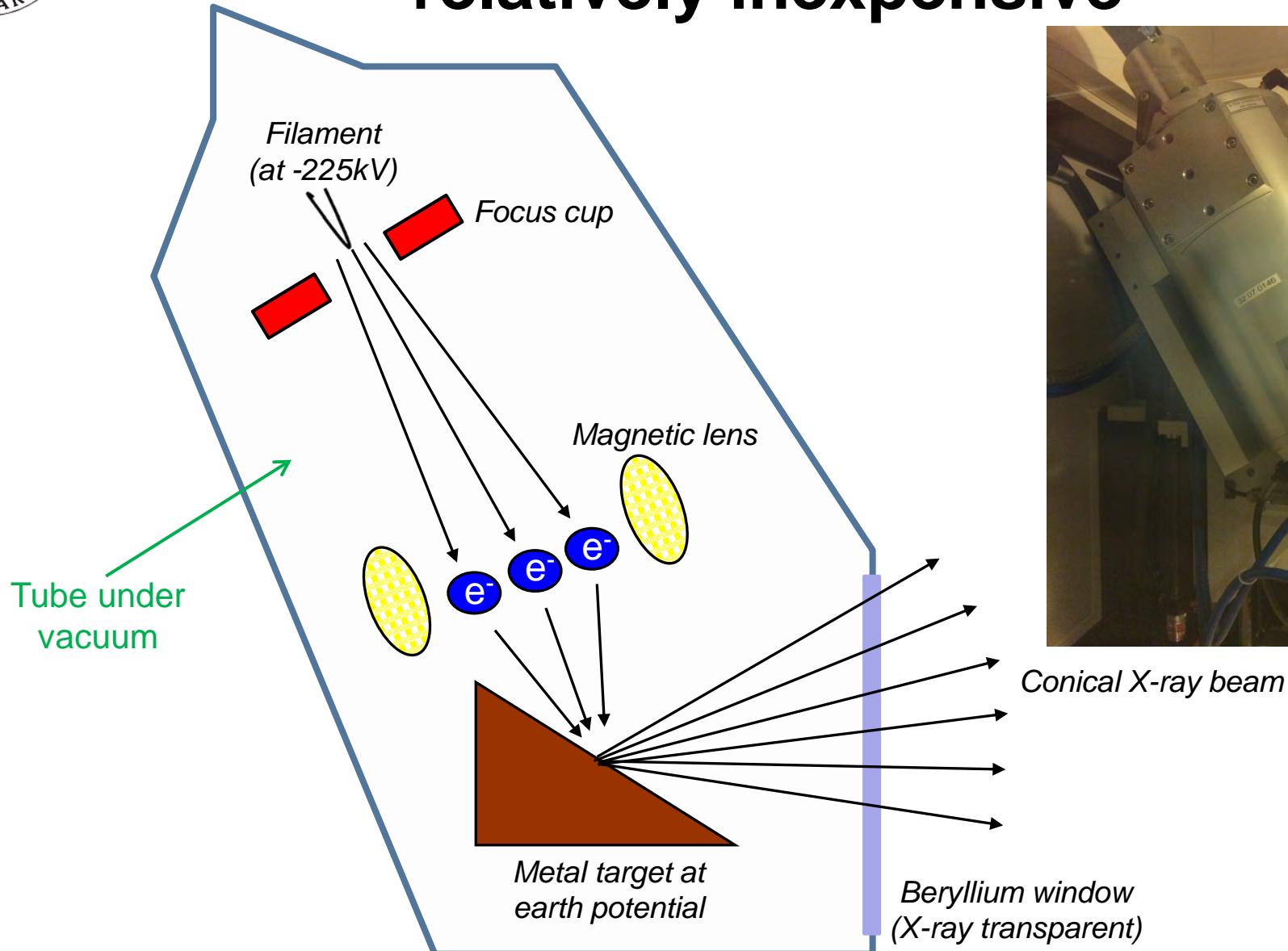
2) Firing electrons at high speed on to a metal target.

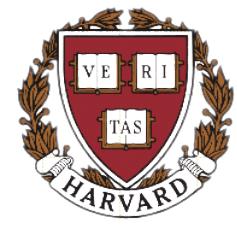
- Electrons are produced from a hot Tungsten filament (like a light bulb).
- They are accelerated using a high voltage into a beam tube.
- They travel at up to 80% the speed of light (giving them energies of 30 - 450keV).
- They are focused by a magnetic lens into a very small spot ($1-5\mu\text{m}$ diameter) onto the surface of a metal target.
- The sudden deceleration of the charged electrons when they hit the target produces heat (a lot!) and X-rays (some).



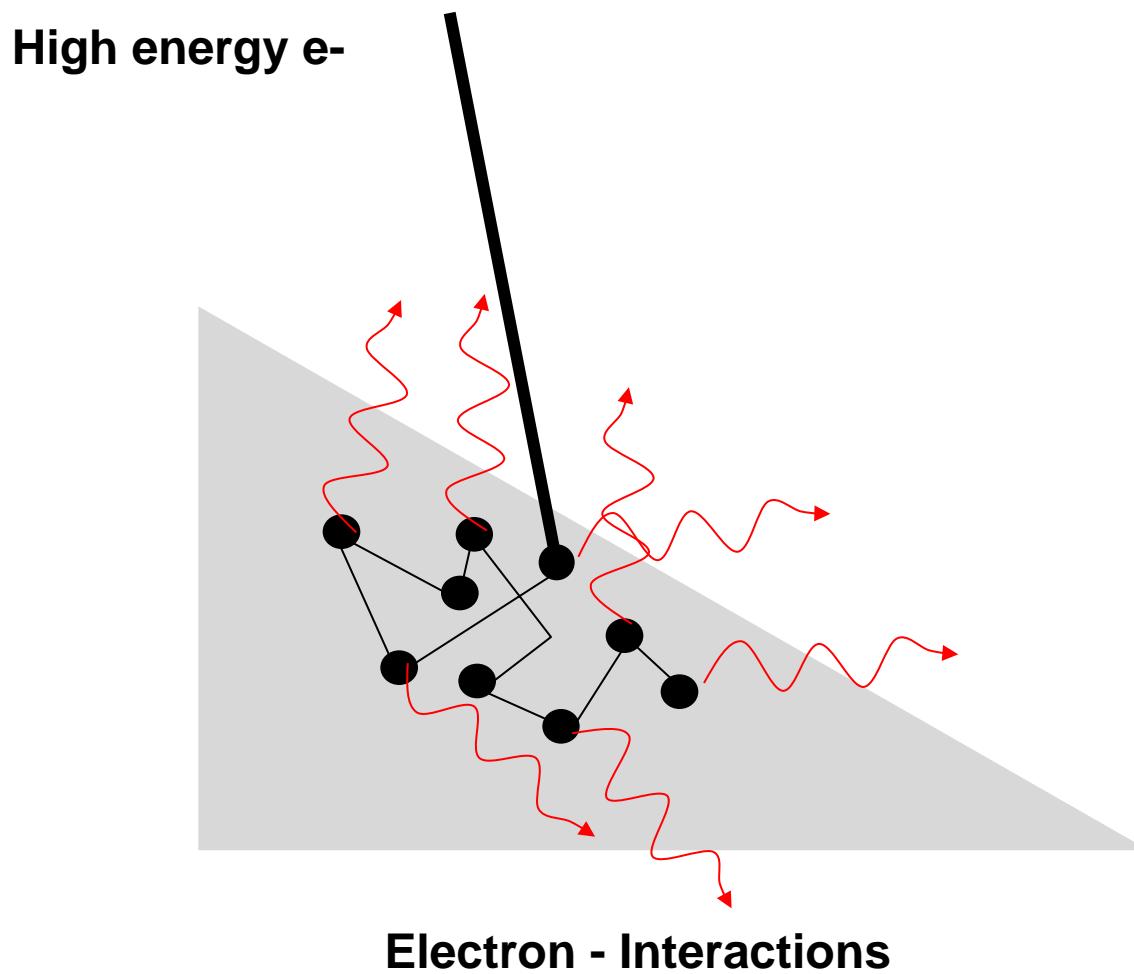


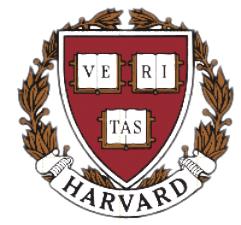
X-ray Tubes: simple and relatively inexpensive



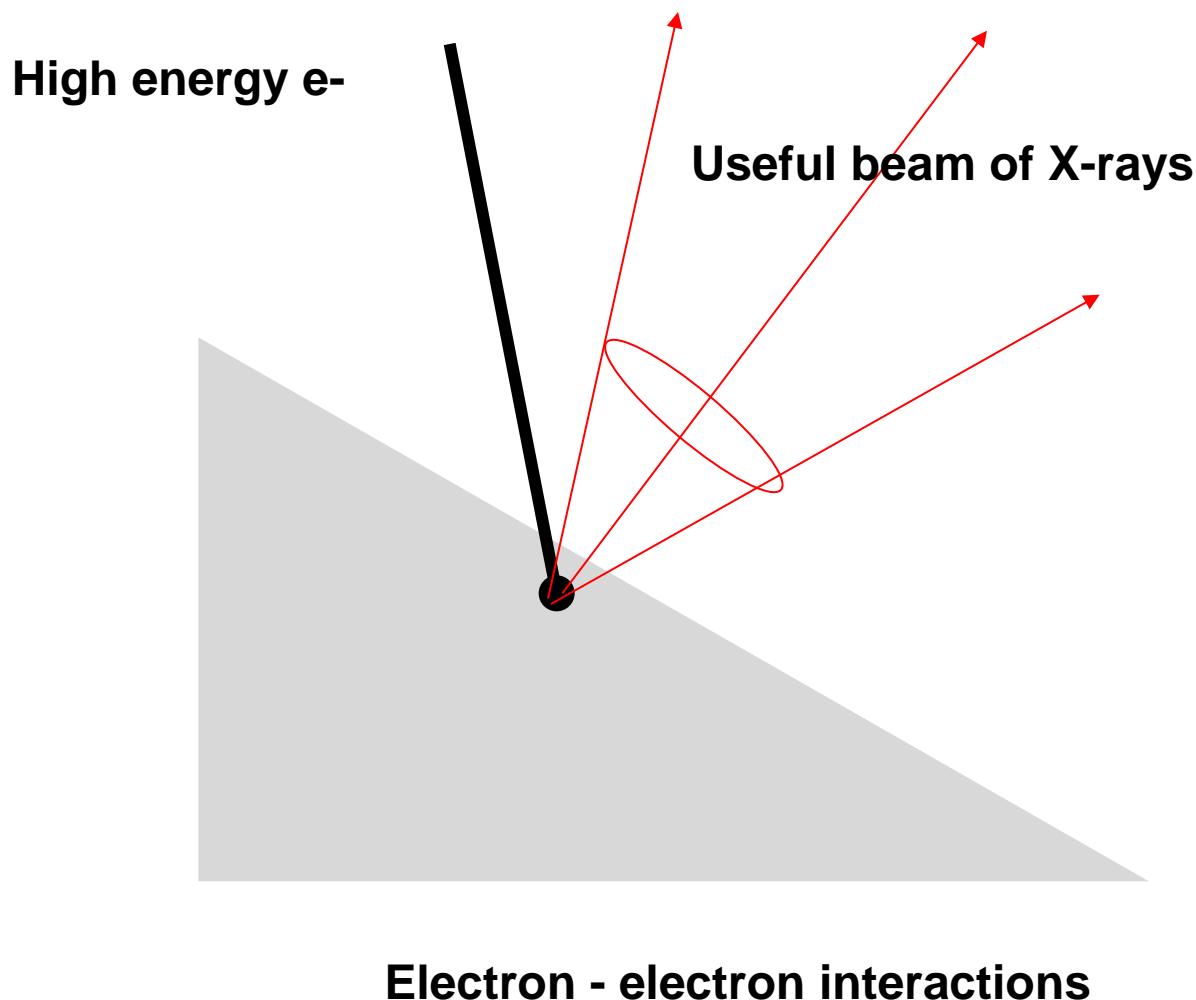


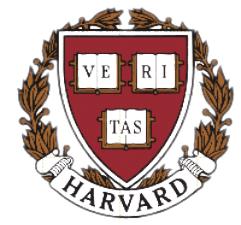
How to generate X-rays?





How to generate X-rays?

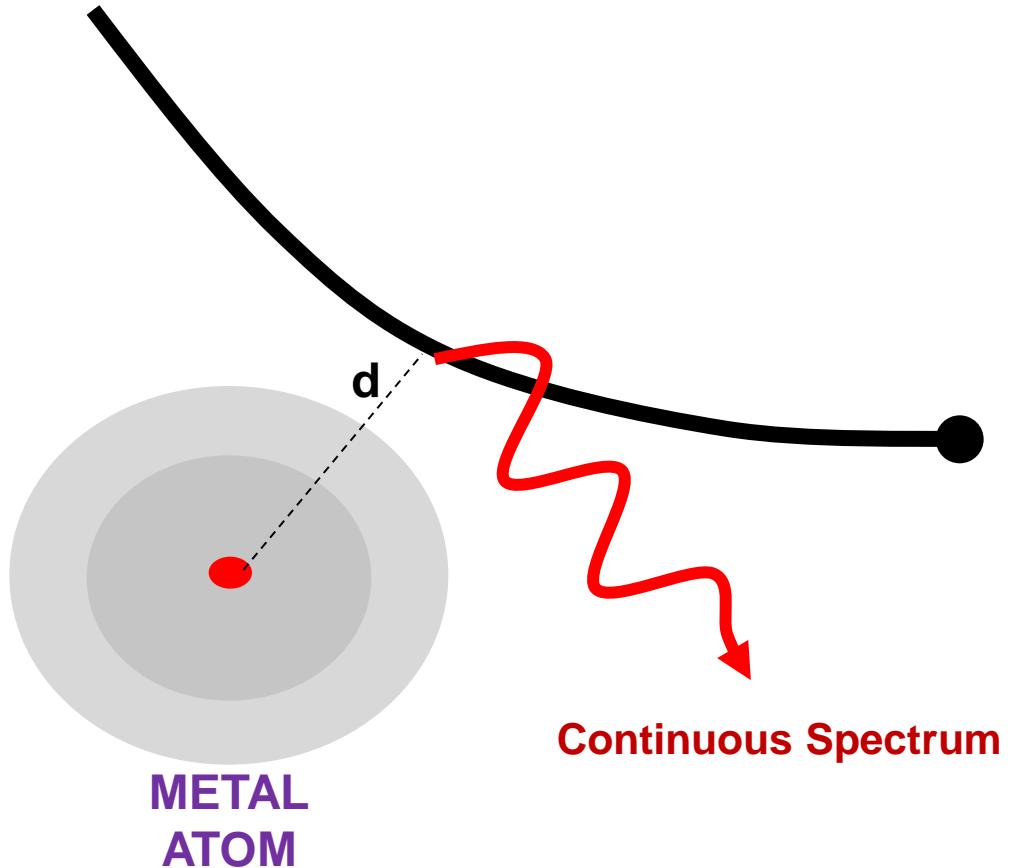


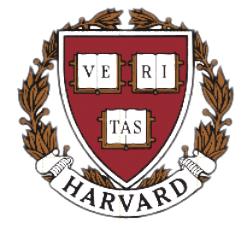


Bremstrahlung

High energy e-
“near miss”

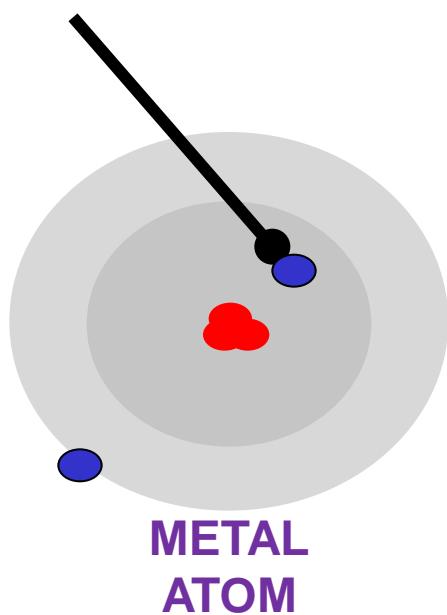
Range of d's
Range of accelerations
Range of photon energies
Continuum radiation



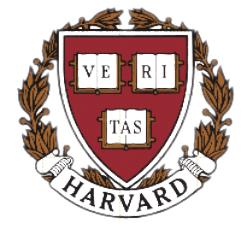


Characteristic Radiation

High energy e-
“collision”

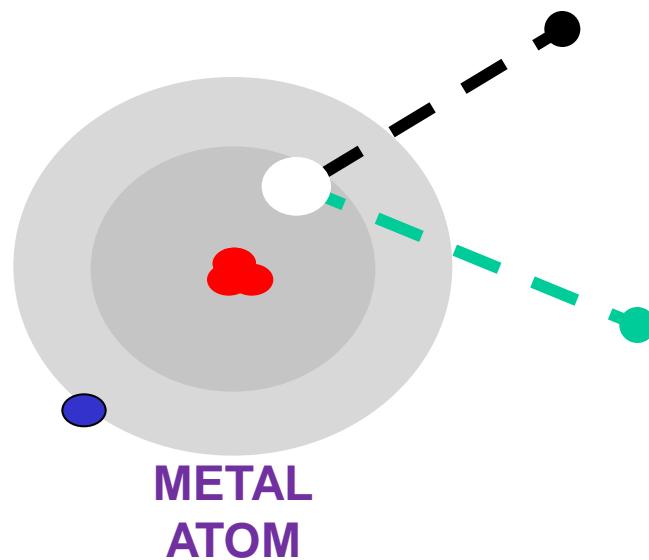


METAL
ATOM



Characteristic Radiation

The Collision removes an electron from the atom



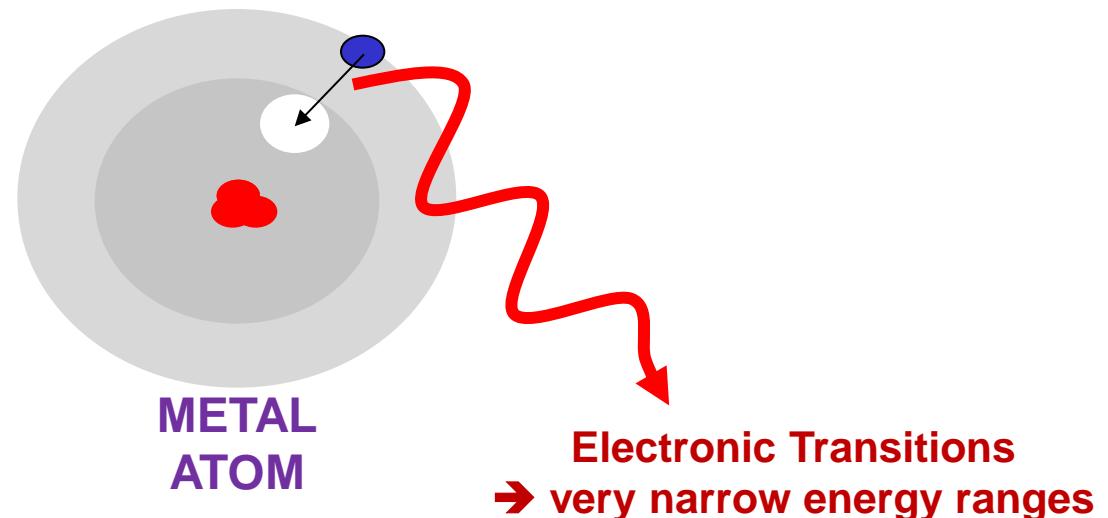
METAL
ATOM



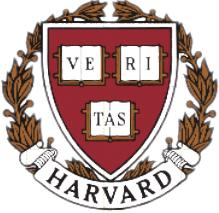
Characteristic Radiation

An outer electron falls to fill the “hole” and an X-ray photon emitted.

Photon Energy = difference between the initial and final state of the transition.



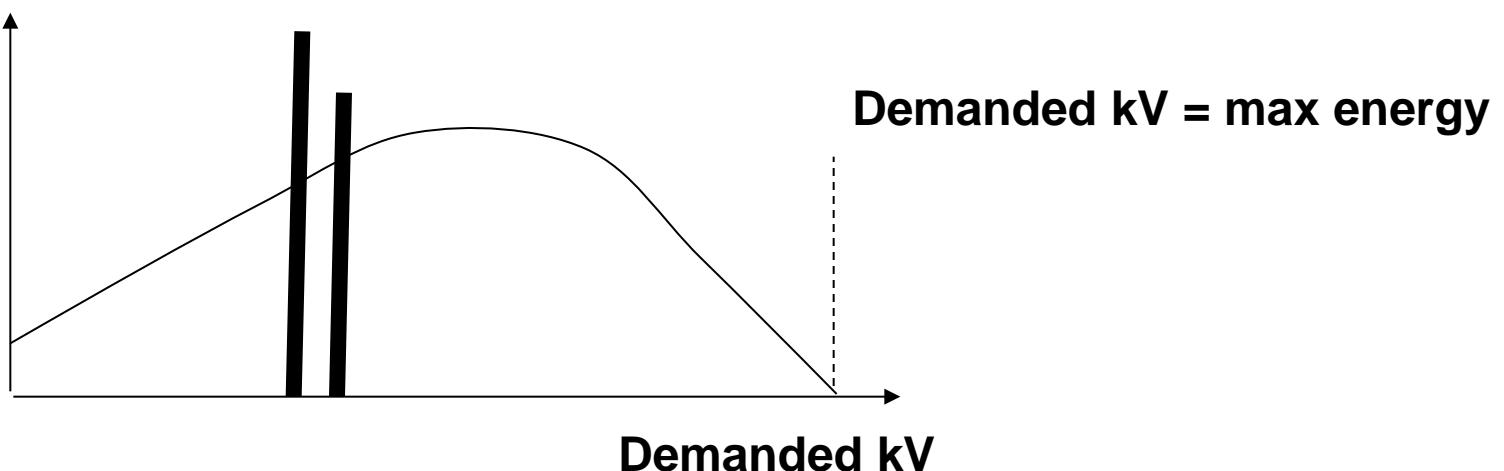
Electron states are dependent on the material
Hence – characteristic X-ray

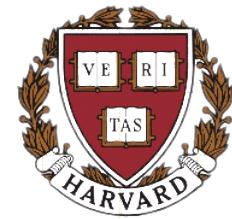


Spectrum from an X-ray Tube

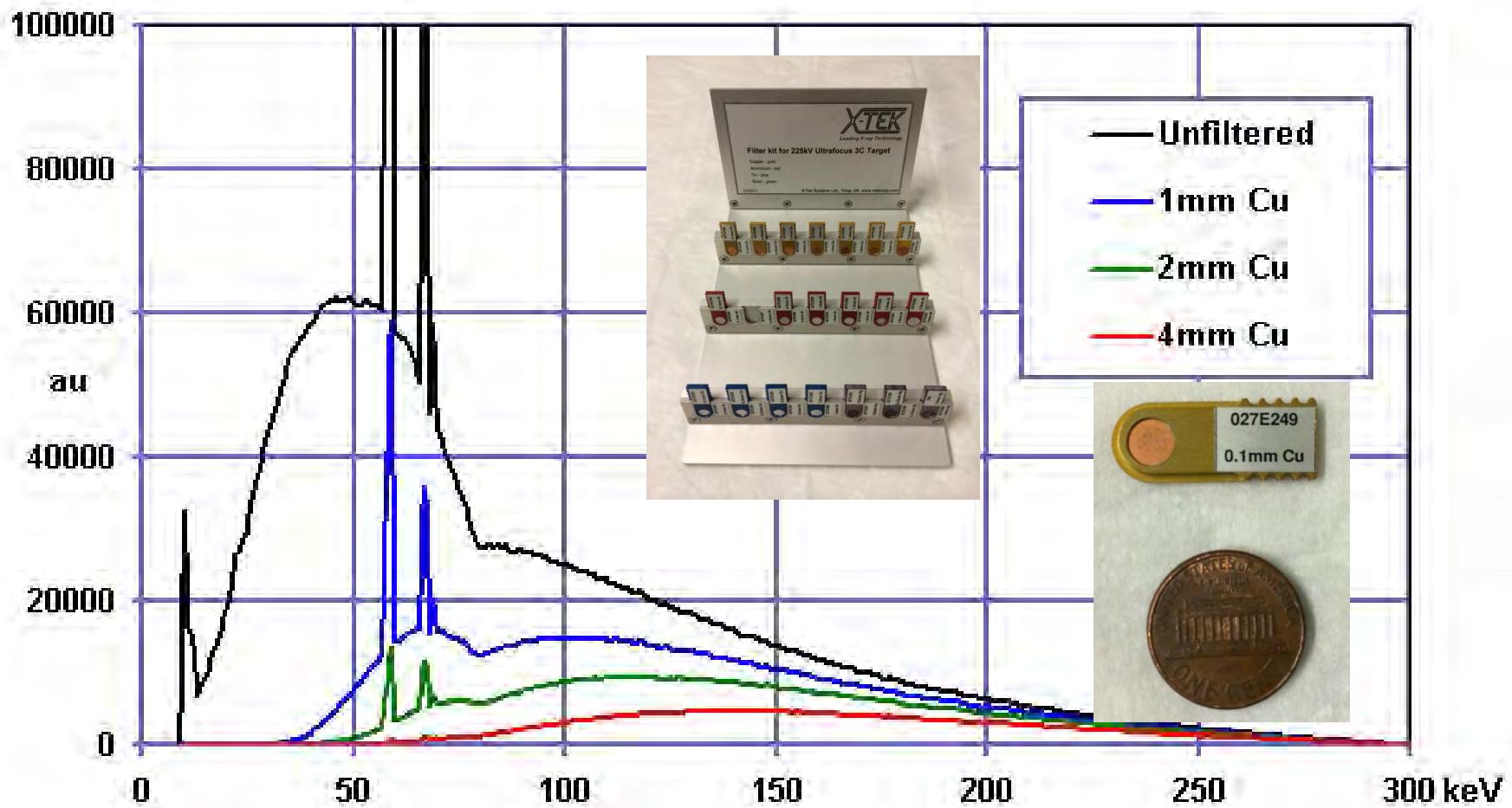
The spectrum from the source is made up of two components

- 1) Continuum radiation ~ 95%
- 2) Characteristic Lines from the target material ~ 5%





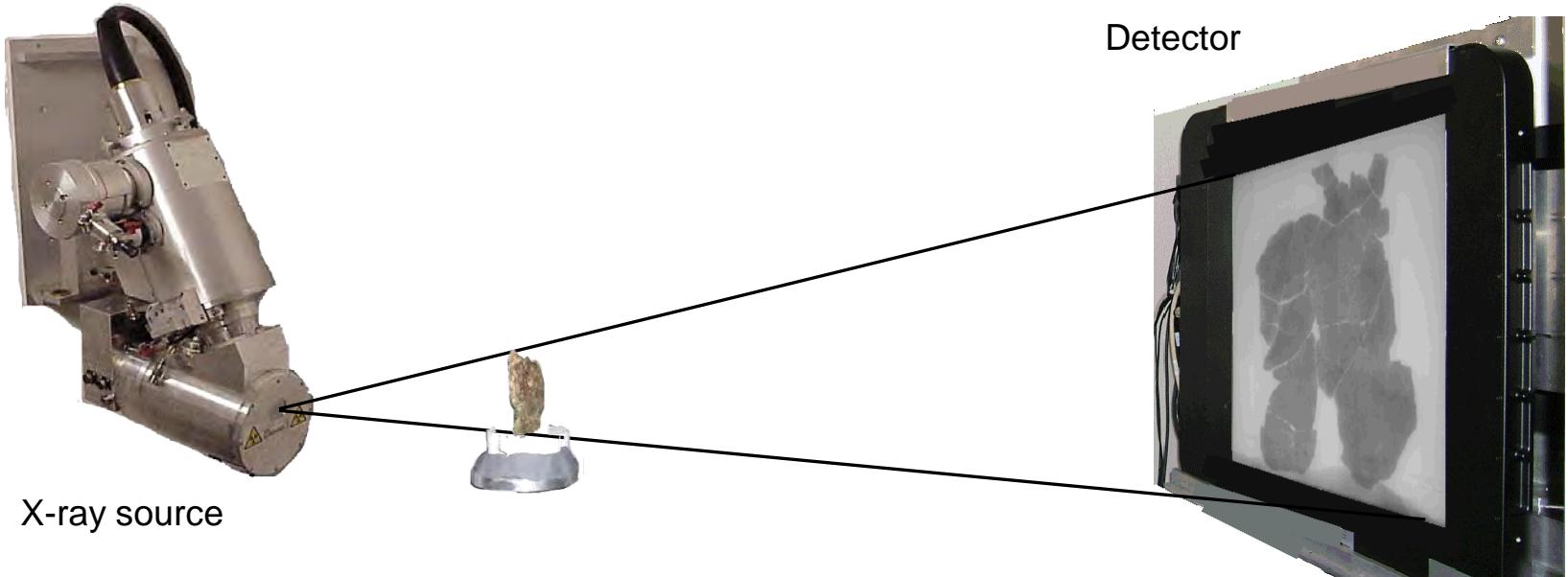
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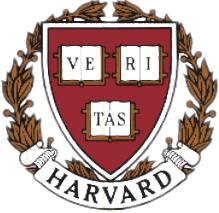


X-ray Imaging

How do we get an X-ray image?

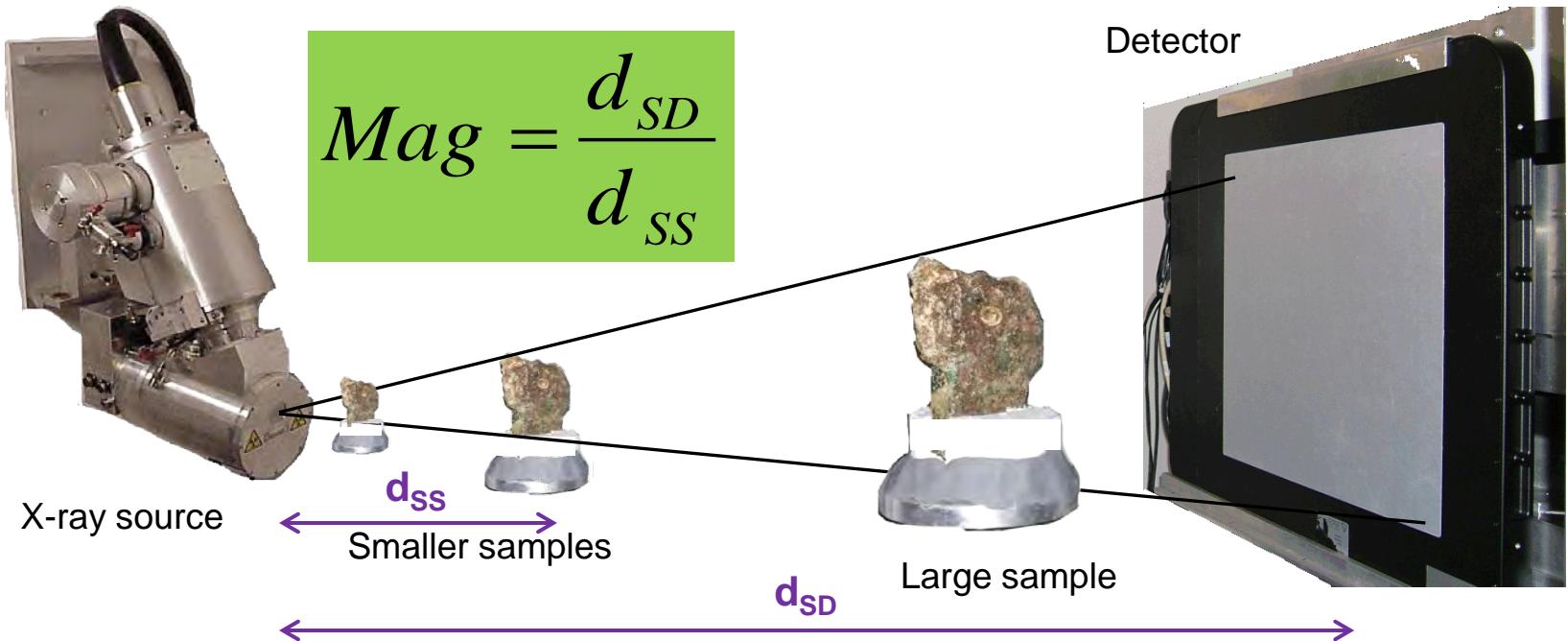


X-rays travel in straight lines and pass right through the sample. However, some of the X-rays are absorbed by the sample and so the intensity of the X-rays is reduced forming a shadow image.



X-ray Imaging

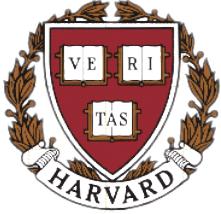
How do we get a magnified image?



Just like light, X-rays travel in straight lines.
Unlike light, we cannot use a lens, so we use geometric magnification.

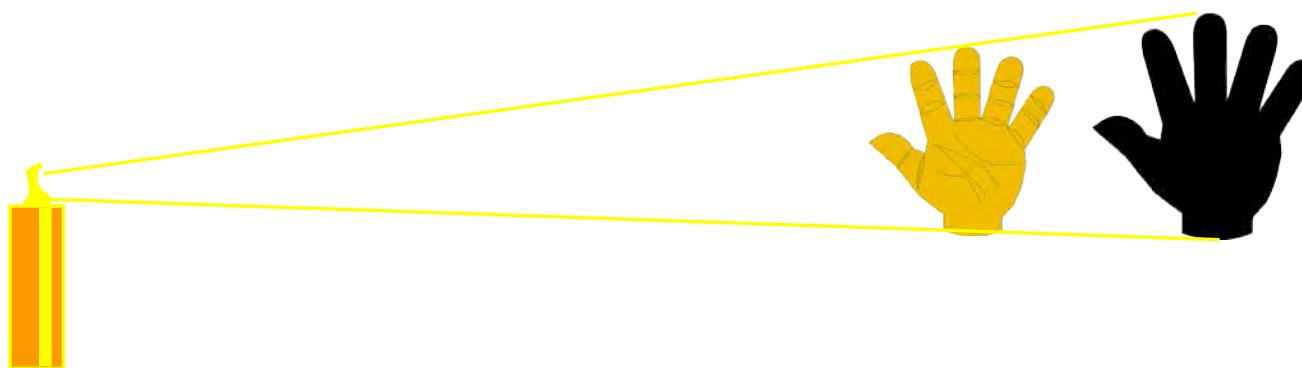
The magnification is increased by moving the sample closer to the X-ray source (and vice versa).

Working distance increases as sample size increases → Mag decreases!

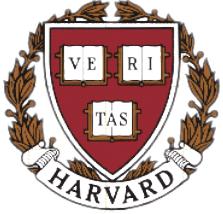


X-ray Imaging

How do we magnify the image?

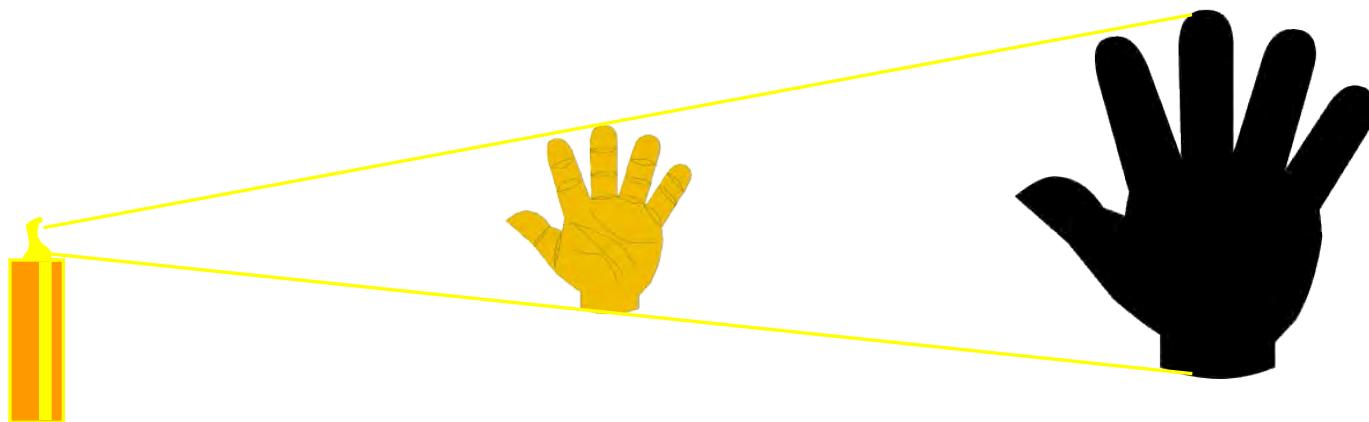


An optical analogy is the shadow cast by your hand on a wall by the light of a candle. As you move your hand closer to the candle, the shadow on the wall will get larger.

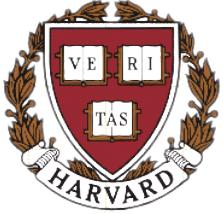


X-ray Imaging

How do we magnify the image?

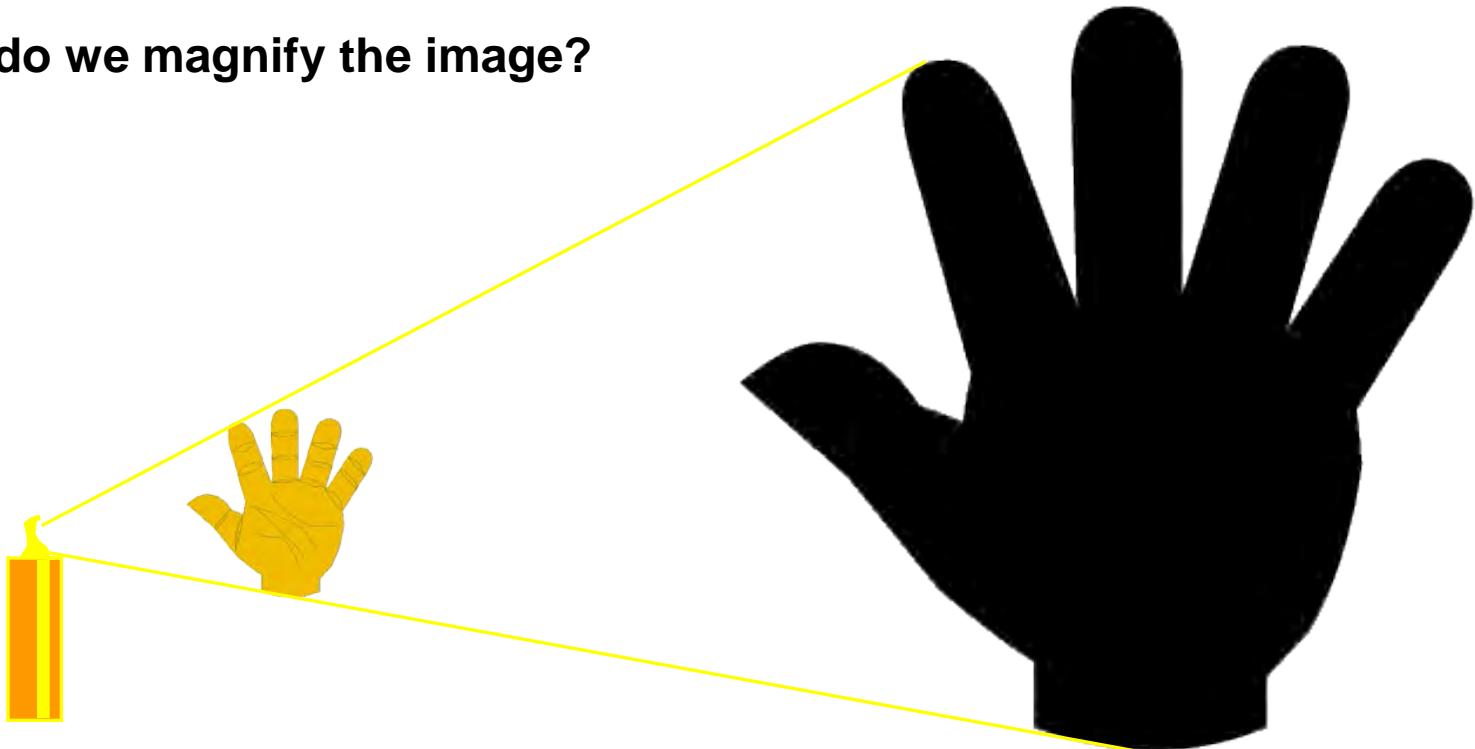


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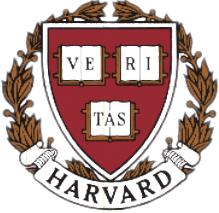


X-ray Imaging

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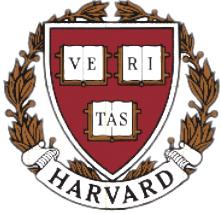
X-ray Imaging

How do we image the X-rays?

- When X-rays hit certain materials, they cause them to fluoresce. In this process, the energy of the X-ray is absorbed and re-emitted as visible light. Usually this light is very faint and needs to be amplified, else very sensitive detectors need to be used.
- An image intensifier is coated with a fluorescent front screen which is intensified electronically on to the back screen. A CCD camera with typically 1000x1000 pixels views this back screen. The signal from this camera is digitised to an 8/10 or 12-bit image.

A 150mm image intensifier with a CCD video camera attached





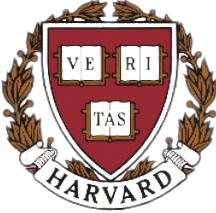
X-ray Imaging

How do we image the X-rays?

- The silicon flat panel detector has a fluorescent screen which converts the X-ray energy into light to form an image on an array of 2000x2000 light-sensitive diodes, each 200x200 μm in size. Electronics allow this image to be read by the computer with a precision of 1 part in 65,536 shades of gray (16 bits).



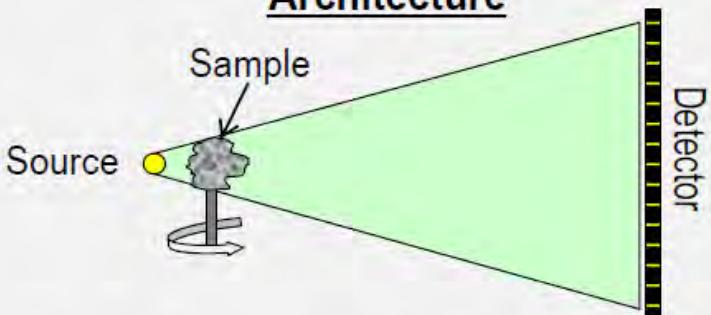
*A 2k x 2k 16-bit
amorphous silicon flat
panel detector from
PerkinElmer*



Imaging Architecture Comparison

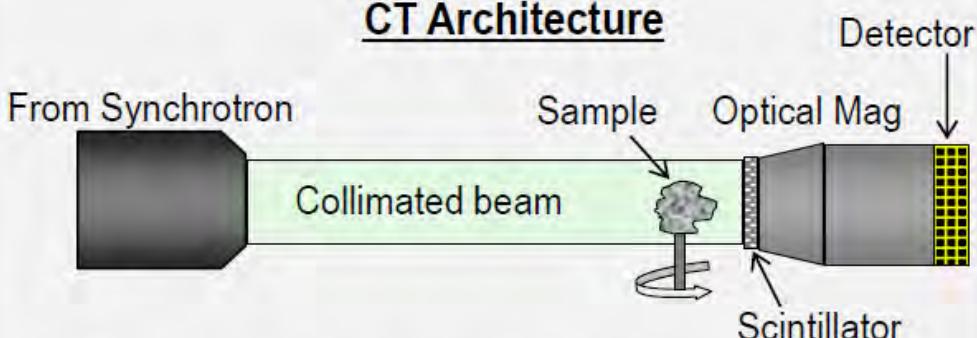
Synchrotron vs. Conventional CT vs. with Optical Magnification

Conventional CT Architecture



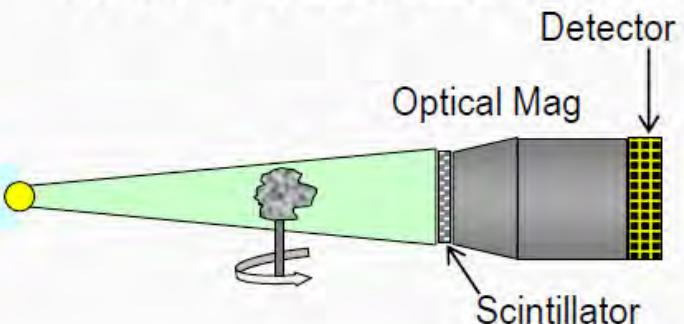
Relies on geometric magnification and small spot size for resolution. Large detector pixel.

Synchrotron Source CT Architecture



Relies on optical magnification/small detector pixel size for resolution. Large spot size.

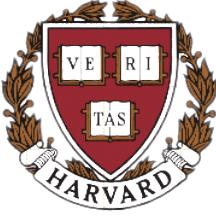
Xradia Versa Architecture:



- ❑ Resolution relies on small detector pixels
- ❑ Achieves high resolution with small geometric magnification
- ❑ Flexibility to use more or less geo mag
- ❑ Does not require small spot size

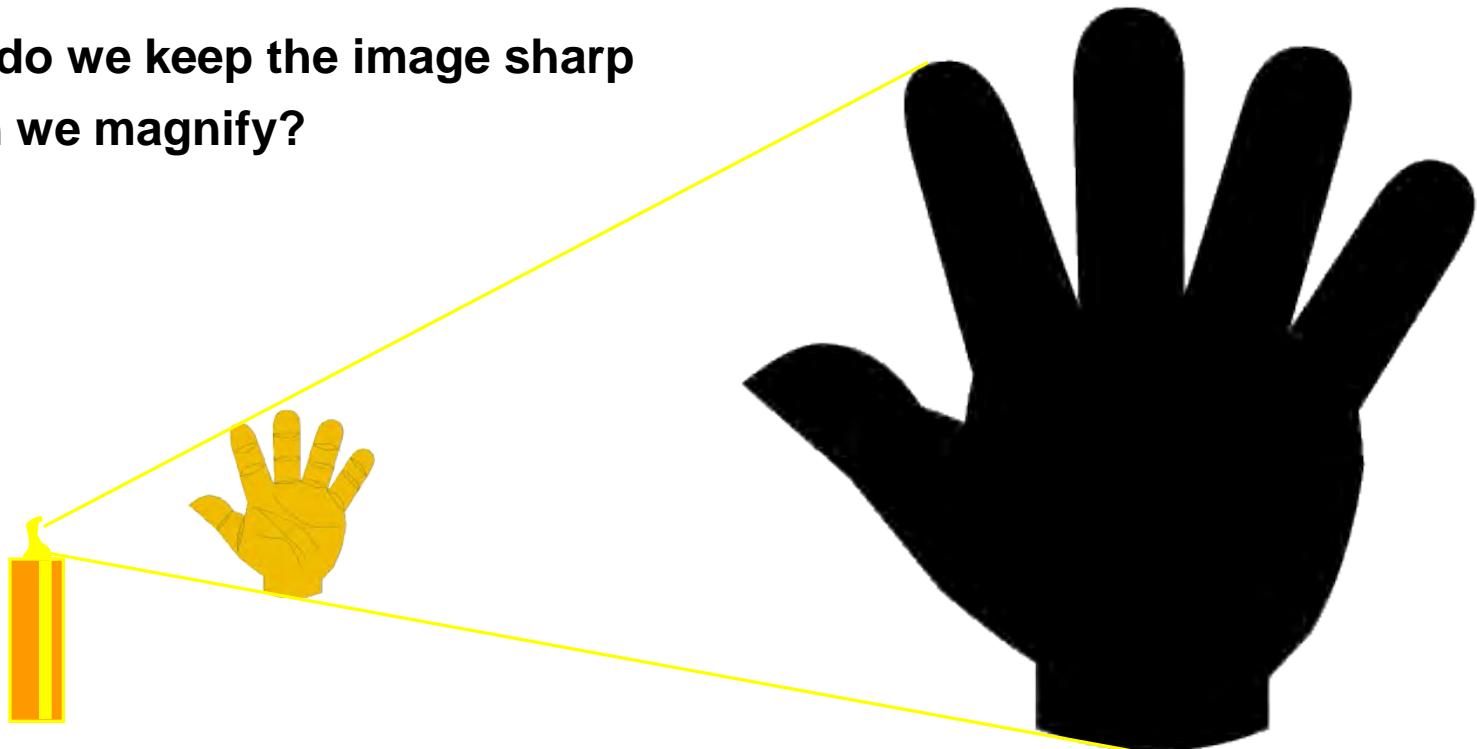


(Credit: Zeiss)

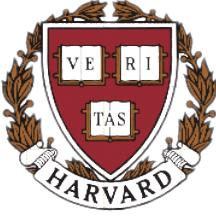


Spot Size dictates max. resolution!

How do we keep the image sharp
when we magnify?

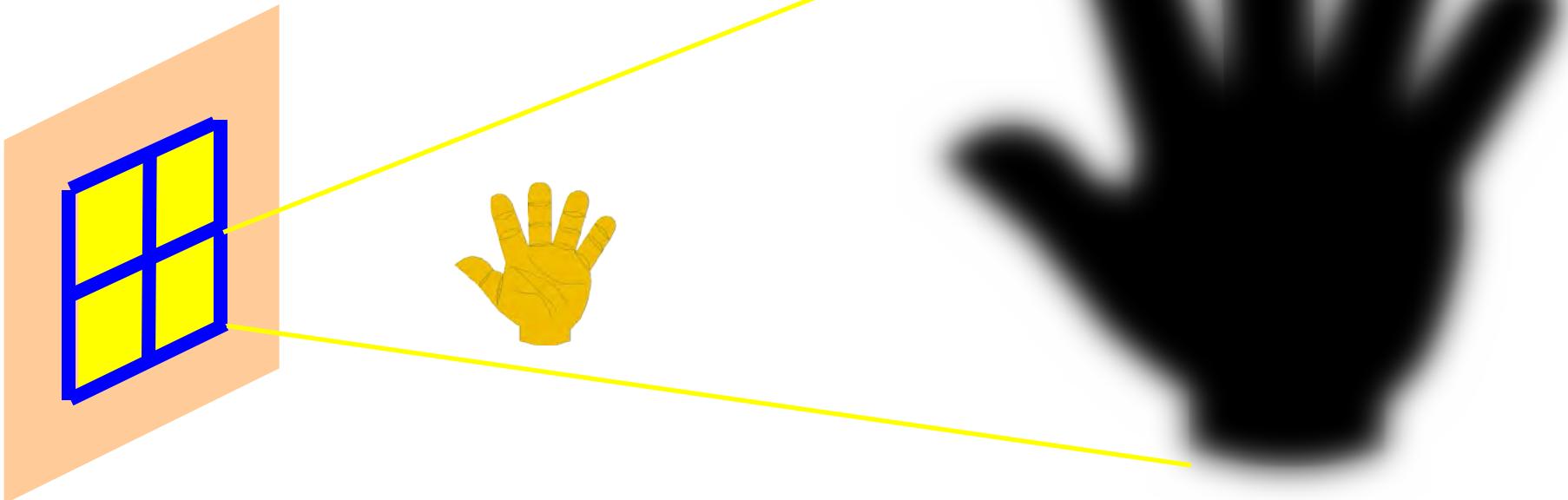


An optical analogy here is the difference between the shadow cast by a small light source, such as a candle and that cast by a larger light source, such as a window.



Spot Size dictates max. resolution!

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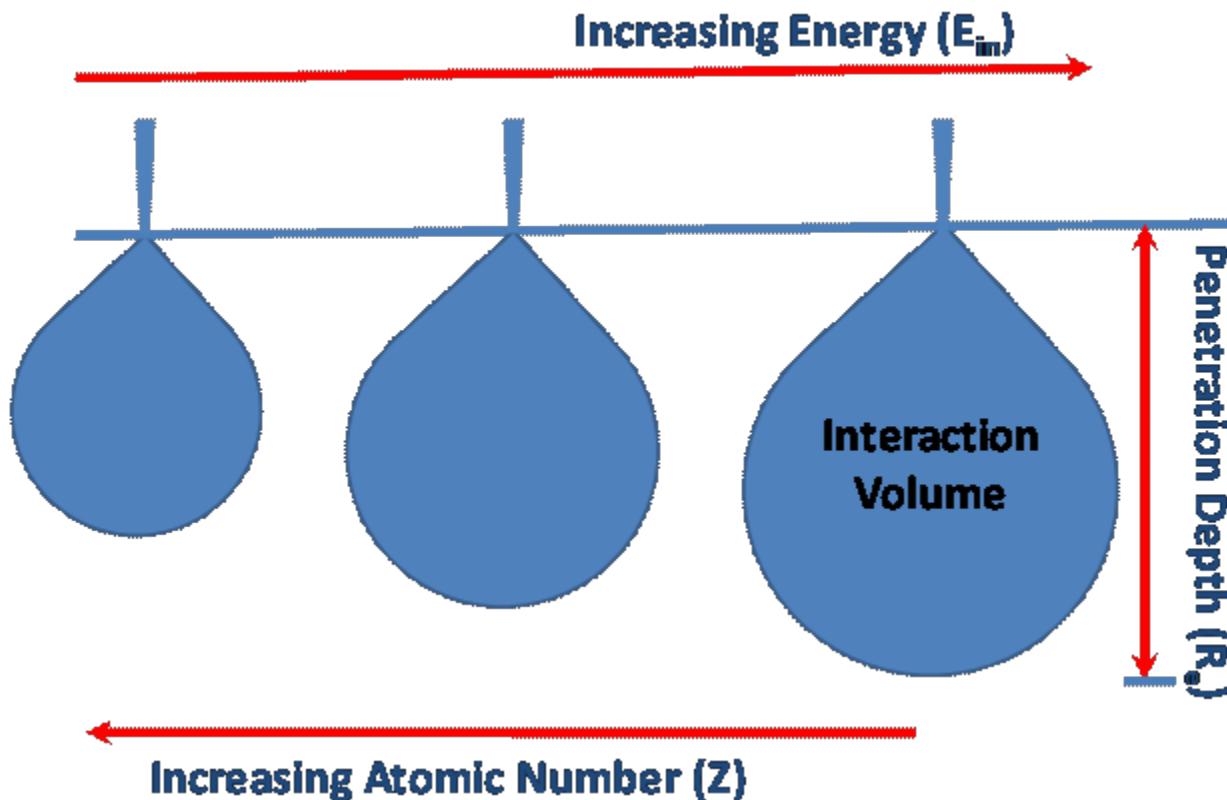
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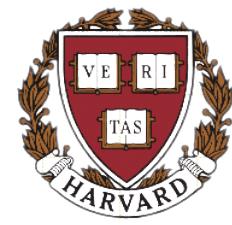


Performance and Resolution

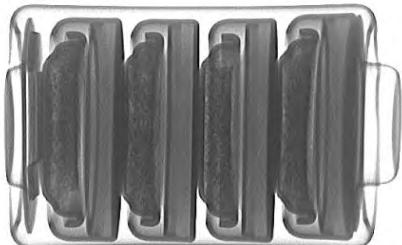
The source (i.e. X-ray spot) size depends on the energy of the electron beam, the X-ray target material, and the target geometry (thin metal layer or water-cooled metal block).

The higher the energy, the larger the interaction volume, hence the larger X-ray spot size, hence the lower the maximum attainable resolution!

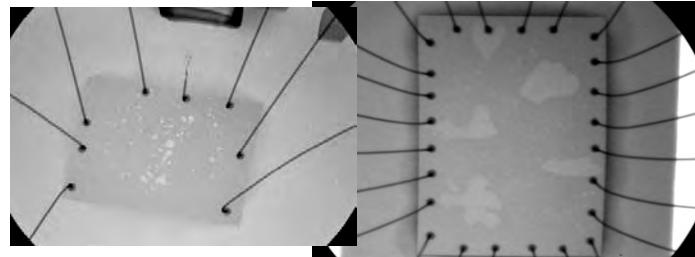




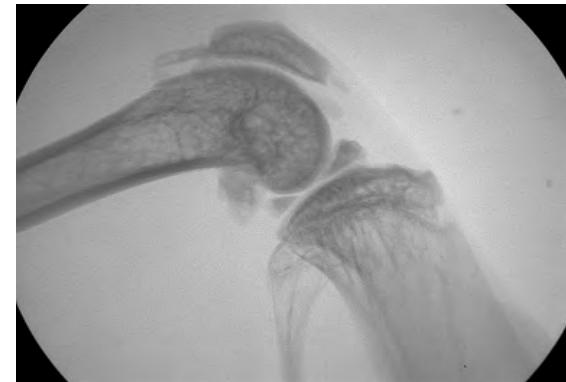
Applications of (2D) X-ray Imaging



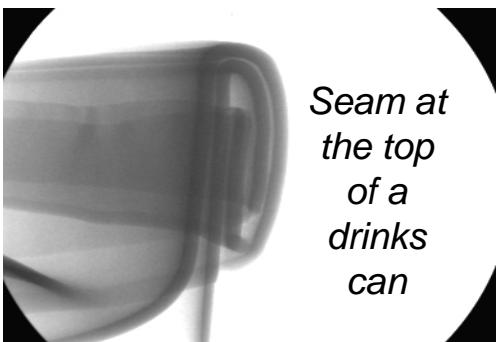
Battery



Electronics

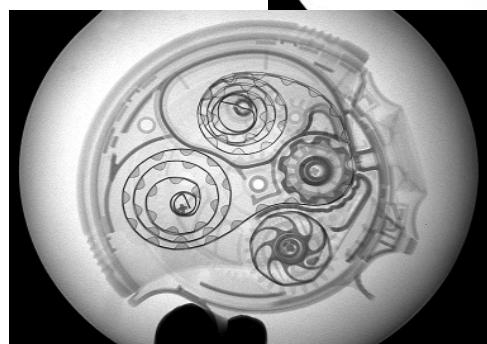


Medical



Seam at
the top
of a
drinks
can

A blown fuse

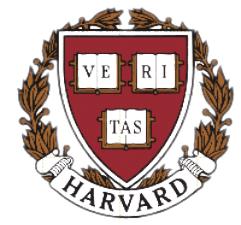


Castings



X-rays can be used to
image many products!

... and complex mechanisms!



Major drawback of 2D X-ray Imaging:

NO SPACIAL INFORMATION IN THE 3RD DIMENSION!

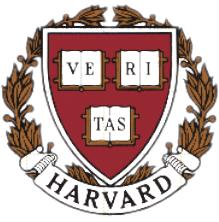
2D X-ray image of Fitbit Flex personal activity monitor



E.g. is this dark structure in front or behind the circuit board?

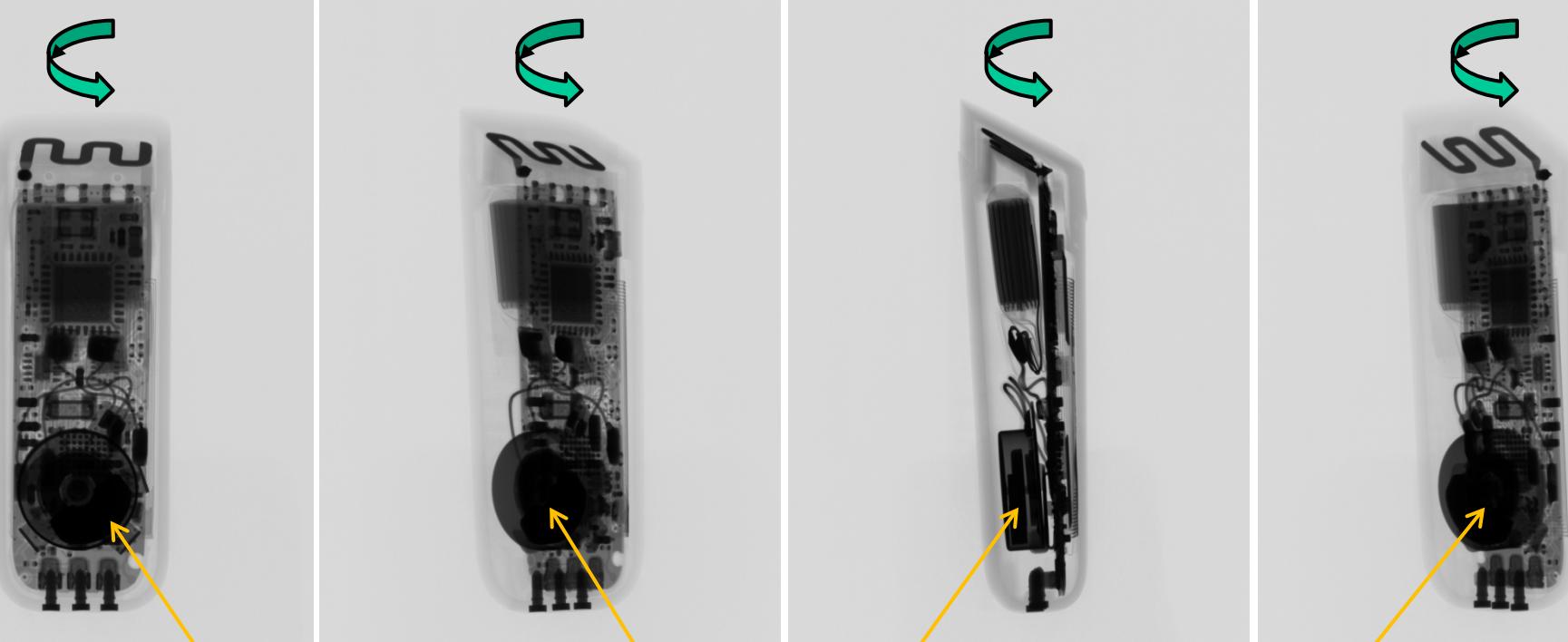
Fitbit Flex personal activity monitor



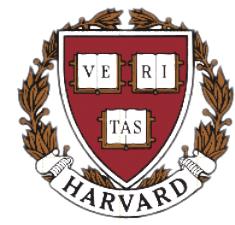


Major drawback of 2D X-ray Imaging:

BUT ONCE WE START ROTATING THE SAMPLE...



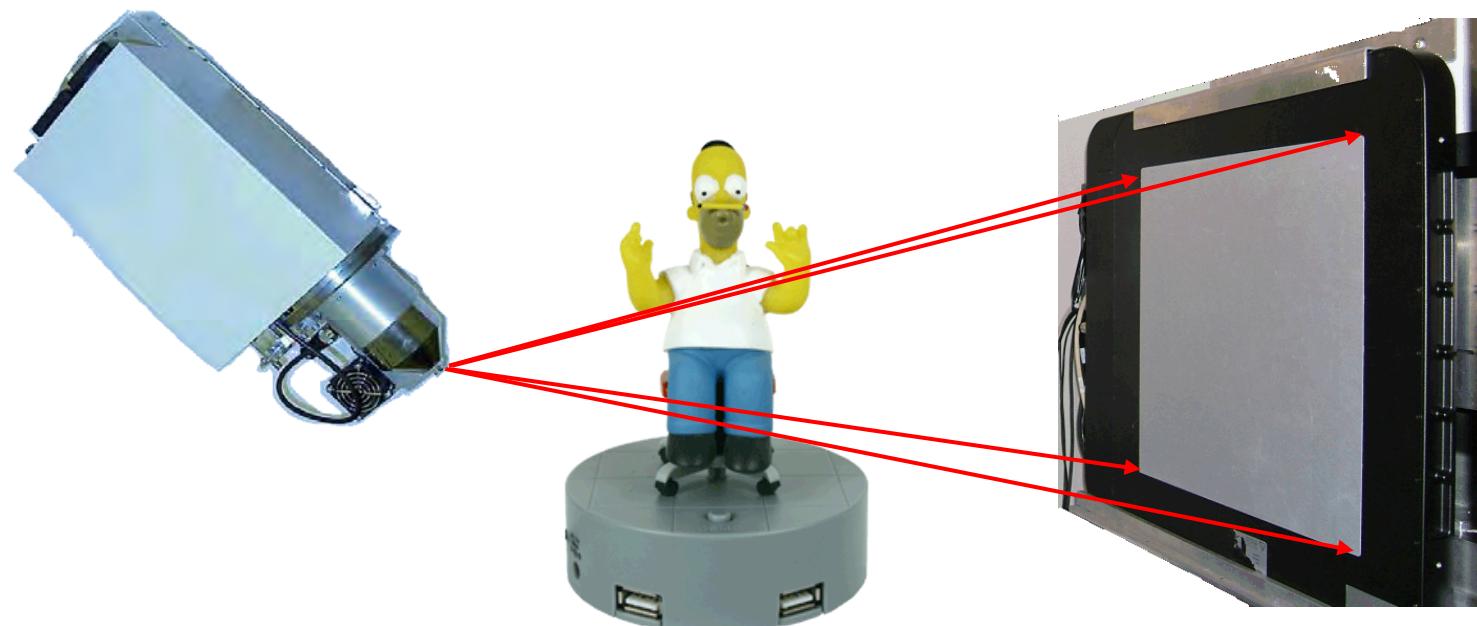
Now we know where this dark structure is w.r.t. the circuit board!

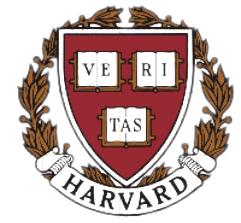


X-ray Computed Tomography

What is X-ray Computed Tomography (or X-ray CT)?

- The process of imaging an object from all directions using penetrating X-rays and using a computer to reconstruct the internal 3-D structure of the object from the intensity values in the projected images.
- It is the process used in a medical CT scanner, though in our case we keep the source and detector stationary and rotate the object.





X-ray Attenuation

How much X-rays get attenuated is material-dependent!



Periodic Table of the Elements																	
1	H	Hydrogen	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	Li	Lithium	3	Be	Boron	4	5	6	7	8	9	10	11	12	13	14	15
3	Na	Sodium	4	Mg	Magnesium	5	6	7	8	9	10	11	12	13	14	15	16
4	K	Potassium	5	Ca	Calcium	6	7	8	9	10	11	12	13	14	15	16	17
5	Rb	Rubidium	6	Sr	Samarium	7	Sc	Titanium	8	21	22	23	24	25	26	27	28
6	Cs	Ce	7	Y	Yttrium	8	9	Zirconium	9	29	30	31	32	33	34	35	36
7	Fr	Ra	8	Hf	Hafnium	9	10	Tantalum	10	37	38	39	40	41	42	43	44
8	89-103	89-103	10	Rf	Rhenium	11	105	Dubnium	12	106	Sg	72	73	74	75	76	77
9	Ac	Th	10	Db	Dubnium	11	Pa	Protactinium	12	107	Bk	W	Os	Ir	Pt	Pb	Bi
10	No	U	10	U	Uranium	11	108	Hs	10	109	Mt	78	79	80	81	82	83
11	Ac	Th	10	U	Uranium	11	109	Hs	10	110	Ds	84	85	86	87	88	89
12	No	U	10	U	Uranium	11	110	Hs	10	111	Rg	84	85	86	87	88	89
13	La	Ce	10	U	Uranium	11	111	Hs	10	112	Cn	85	86	87	88	89	90
14	Pr	Nd	10	U	Uranium	11	112	Hs	10	113	Uut	85	86	87	88	89	91
15	Pm	Sm	10	U	Uranium	11	113	Hs	10	114	Uup	85	86	87	88	89	92
16	Gd	Tb	10	U	Uranium	11	114	Hs	10	115	Uuu	85	86	87	88	89	93
17	Dy	Ho	10	U	Uranium	11	115	Hs	10	116	Uuh	85	86	87	88	89	94
18	Er	Tm	10	U	Uranium	11	116	Hs	10	117	Uus	85	86	87	88	89	95
19	Yb	Lu	10	U	Uranium	11	117	Hs	10	118	Uuo	85	86	87	88	89	96
20	Ac	Th	10	U	Uranium	11	118	Hs	10	119	Uuo	85	86	87	88	89	97
21	Ac	Th	10	U	Uranium	11	119	Hs	10	120	Uuo	85	86	87	88	89	98
22	Ac	Th	10	U	Uranium	11	120	Hs	10	121	Uuo	85	86	87	88	89	99
23	Ac	Th	10	U	Uranium	11	121	Hs	10	122	Uuo	85	86	87	88	89	100
24	Ac	Th	10	U	Uranium	11	122	Hs	10	123	Uuo	85	86	87	88	89	101
25	Ac	Th	10	U	Uranium	11	123	Hs	10	124	Uuo	85	86	87	88	89	102
26	Ac	Th	10	U	Uranium	11	124	Hs	10	125	Uuo	85	86	87	88	89	103
27	Ac	Th	10	U	Uranium	11	125	Hs	10	126	Uuo	85	86	87	88	89	104
28	Ac	Th	10	U	Uranium	11	126	Hs	10	127	Uuo	85	86	87	88	89	105
29	Ac	Th	10	U	Uranium	11	127	Hs	10	128	Uuo	85	86	87	88	89	106
30	Ac	Th	10	U	Uranium	11	128	Hs	10	129	Uuo	85	86	87	88	89	107
31	Ac	Th	10	U	Uranium	11	129	Hs	10	130	Uuo	85	86	87	88	89	108
32	Ac	Th	10	U	Uranium	11	130	Hs	10	131	Uuo	85	86	87	88	89	109
33	Ac	Th	10	U	Uranium	11	131	Hs	10	132	Uuo	85	86	87	88	89	110
34	Ac	Th	10	U	Uranium	11	132	Hs	10	133	Uuo	85	86	87	88	89	111
35	Ac	Th	10	U	Uranium	11	133	Hs	10	134	Uuo	85	86	87	88	89	112
36	Ac	Th	10	U	Uranium	11	134	Hs	10	135	Uuo	85	86	87	88	89	113
37	Ac	Th	10	U	Uranium	11	135	Hs	10	136	Uuo	85	86	87	88	89	114
38	Ac	Th	10	U	Uranium	11	136	Hs	10	137	Uuo	85	86	87	88	89	115
39	Ac	Th	10	U	Uranium	11	137	Hs	10	138	Uuo	85	86	87	88	89	116
40	Ac	Th	10	U	Uranium	11	138	Hs	10	139	Uuo	85	86	87	88	89	117
41	Ac	Th	10	U	Uranium	11	139	Hs	10	140	Uuo	85	86	87	88	89	118
42	Ac	Th	10	U	Uranium	11	140	Hs	10	141	Uuo	85	86	87	88	89	119
43	Ac	Th	10	U	Uranium	11	141	Hs	10	142	Uuo	85	86	87	88	89	120
44	Ac	Th	10	U	Uranium	11	142	Hs	10	143	Uuo	85	86	87	88	89	121
45	Ac	Th	10	U	Uranium	11	143	Hs	10	144	Uuo	85	86	87	88	89	122
46	Ac	Th	10	U	Uranium	11	144	Hs	10	145	Uuo	85	86	87	88	89	123
47	Ac	Th	10	U	Uranium	11	145	Hs	10	146	Uuo	85	86	87	88	89	124
48	Ac	Th	10	U	Uranium	11	146	Hs	10	147	Uuo	85	86	87	88	89	125
49	Ac	Th	10	U	Uranium	11	147	Hs	10	148	Uuo	85	86	87	88	89	126
50	Ac	Th	10	U	Uranium	11	148	Hs	10	149	Uuo	85	86	87	88	89	127
51	Ac	Th	10	U	Uranium	11	149	Hs	10	150	Uuo	85	86	87	88	89	128
52	Ac	Th	10	U	Uranium	11	150	Hs	10	151	Uuo	85	86	87	88	89	129
53	Ac	Th	10	U	Uranium	11	151	Hs	10	152	Uuo	85	86	87	88	89	130
54	Ac	Th	10	U	Uranium	11	152	Hs	10	153	Uuo	85	86	87	88	89	131
55	Ac	Th	10	U	Uranium	11	153	Hs	10	154	Uuo	85	86	87	88	89	132
56	Ac	Th	10	U	Uranium	11	154	Hs	10	155	Uuo	85	86	87	88	89	133
57	Ac	Th	10	U	Uranium	11	155	Hs	10	156	Uuo	85	86	87	88	89	134
58	Ac	Th	10	U	Uranium	11	156	Hs	10	157	Uuo	85	86	87	88	89	135
59	Ac	Th	10	U	Uranium	11	157	Hs	10	158	Uuo	85	86	87	88	89	136
60	Ac	Th	10	U	Uranium	11	158	Hs	10	159	Uuo	85	86	87	88	89	137
61	Ac	Th	10	U	Uranium	11	159	Hs	10	160	Uuo	85	86	87	88	89	138
62	Ac	Th	10	U	Uranium	11	160	Hs	10	161	Uuo	85	86	87	88	89	139
63	Ac	Th	10	U	Uranium	11	161	Hs	10	162	Uuo	85	86	87	88	89	140
64	Ac	Th	10	U	Uranium	11	162	Hs	10	163	Uuo	85	86	87	88	89	141
65	Ac	Th	10	U	Uranium	11	163	Hs	10	164	Uuo	85	86	87	88	89	142
66	Ac	Th	10	U	Uranium	11	164	Hs	10	165	Uuo	85	86	87	88	89	143
67	Ac	Th	10	U	Uranium	11	165	Hs	10	166	Uuo	85	86	87	88	89	144
68	Ac	Th	10	U	Uranium	11	166	Hs	10	167	Uuo	85	86	87	88	89	145
69	Ac	Th	10	U	Uranium	11	167	Hs	10	168	Uuo	85	86	87	88	89	146
70	Ac	Th	10	U	Uranium	11	168	Hs	10	169	Uuo	85	86	87	88	89	147
71	Ac	Th	10	U	Uranium	11	169	Hs	10	170	Uuo	85	86	87	88	89	148
72	Ac	Th	10	U	Uranium	11	170	Hs	10	171	Uuo	85	86	87	88	89	149
73	Ac	Th	10	U	Uranium	11	171	Hs	10	172	Uuo	85	86	87	88	89	150
74	Ac	Th	10	U	Uranium	11	172	Hs	10	173	Uuo	85	86	87	88	89	151
75	Ac	Th	10	U	Uranium	11	173	Hs	10	174	Uuo	85	86	87	88	89	152
76	Ac	Th	10	U	Uranium	11	174	Hs	10	175	Uuo	85	86	87	88	89	153
77	Ac	Th	10	U	Uranium	11	175	Hs	10	176	Uuo	85	86	87	88	89	154
78	Ac	Th	10	U	Uranium	11	176	Hs	10	177	Uuo	85	86	87	88	89	155
79	Ac	Th	10	U	Uranium	11	177	Hs	10	178	Uuo	85	86	87	88	89	156
80	Ac	Th	10	U	Uranium	11	178	Hs	10	179	Uuo	85	86	87	88	89	157
81	Ac	Th	10	U	Uranium	11	179	Hs	10	180	Uuo	85	86	87	88	89	158
82	Ac	Th	10	U	Uranium	11	180	Hs	10	181	Uuo	85	86	87	88	89	159
83	Ac	Th	10	U	Uranium	11	181	Hs	10	182	Uuo	85	86	87	88	89	160
84	Ac	Th	10	U	Uranium	11	182	Hs	10	183	Uuo	85	86	87	88	89	161
85	Ac	Th	10	U	Uranium	11	183	Hs	10	184	Uuo	85	86	87	88	89	162
86	Ac	Th	10	U	Uranium	11	184	Hs	10	185	Uuo	85	86	87	88	89	163
87	Ac	Th	10	U	Uranium	11	185	Hs	10	186	Uuo	85	86	87	88	89	164
88	Ac	Th	10	U	Uranium	11	186	Hs	10	187	Uuo						



X-ray Computed Tomography

What do CT volumes measure?

The CT volumes measure *X-ray linear attenuation*. This is how much one unit of length of material reduces the X-ray intensity. It is usually measured as a logarithmic value, μ , and is in units of inverse length (e.g. mm^{-1}).

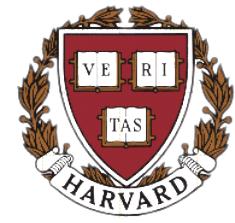
$$I_{\text{measured}} = I_{\text{black}} + (I_{\text{white}} - I_{\text{black}}) \cdot \exp(-\mu t) \quad [t = \text{material thickness}]$$

$$\text{So, } \mu = \ln \{ (I_{\text{white}} - I_{\text{black}}) / (I_{\text{measured}} - I_{\text{black}}) \} / t$$

We have black and white reference images, so we can calculate $\mu \cdot t$ for all projection image pixels.

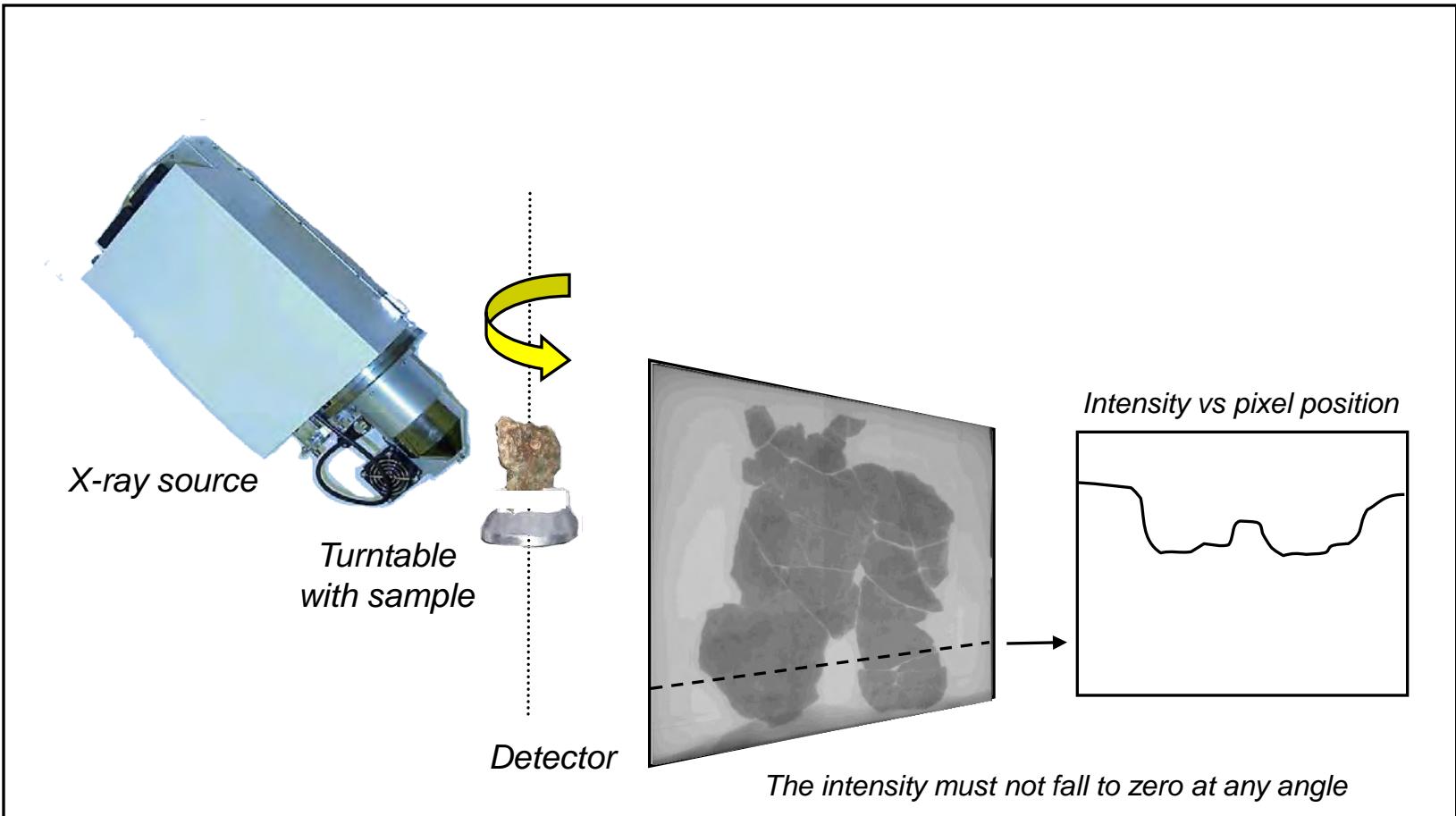
When we reconstruct the volumes, we show the values of μ for all voxels.

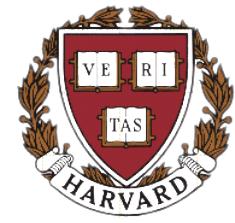
- Think of μ as the *X-ray density* of the material.



X-ray Computed Tomography

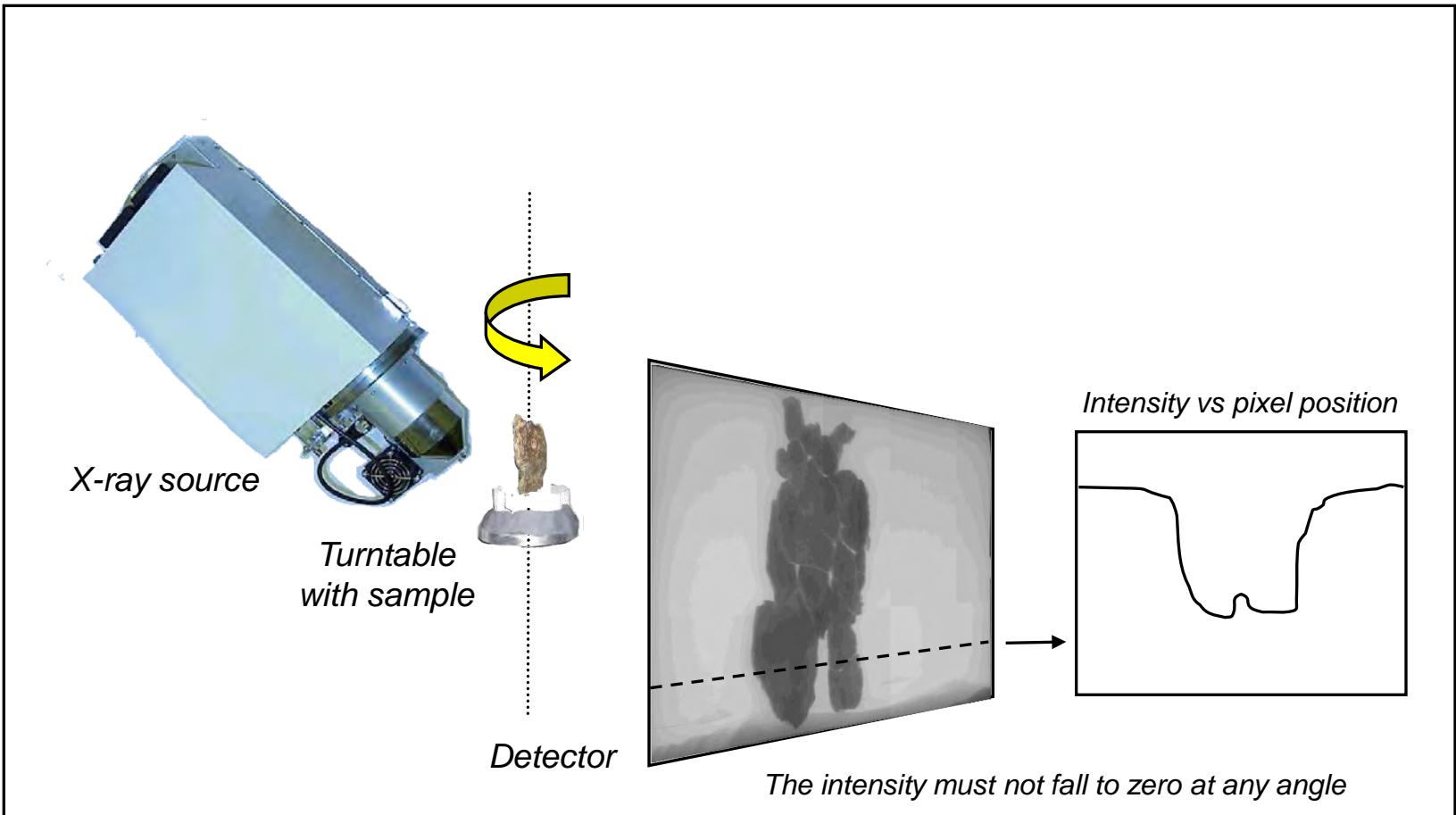
CT requires us to penetrate the object with X-rays from all directions:

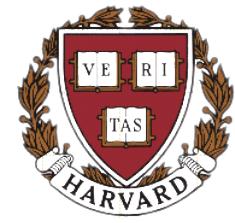




X-ray Computed Tomography

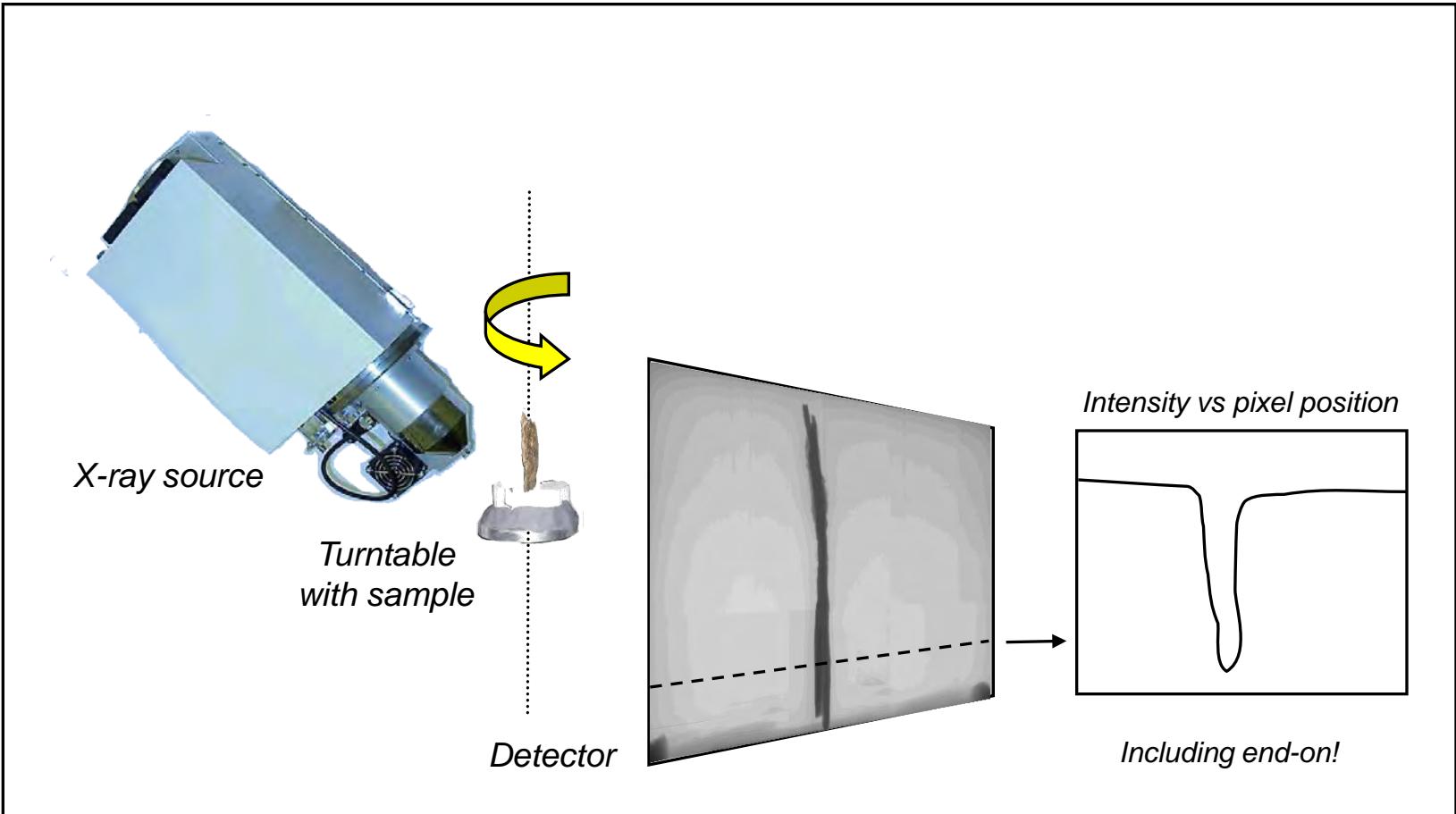
CT requires us to penetrate the object with X-rays from all directions:

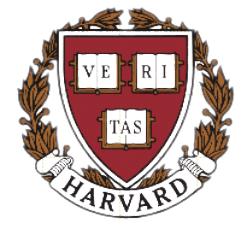




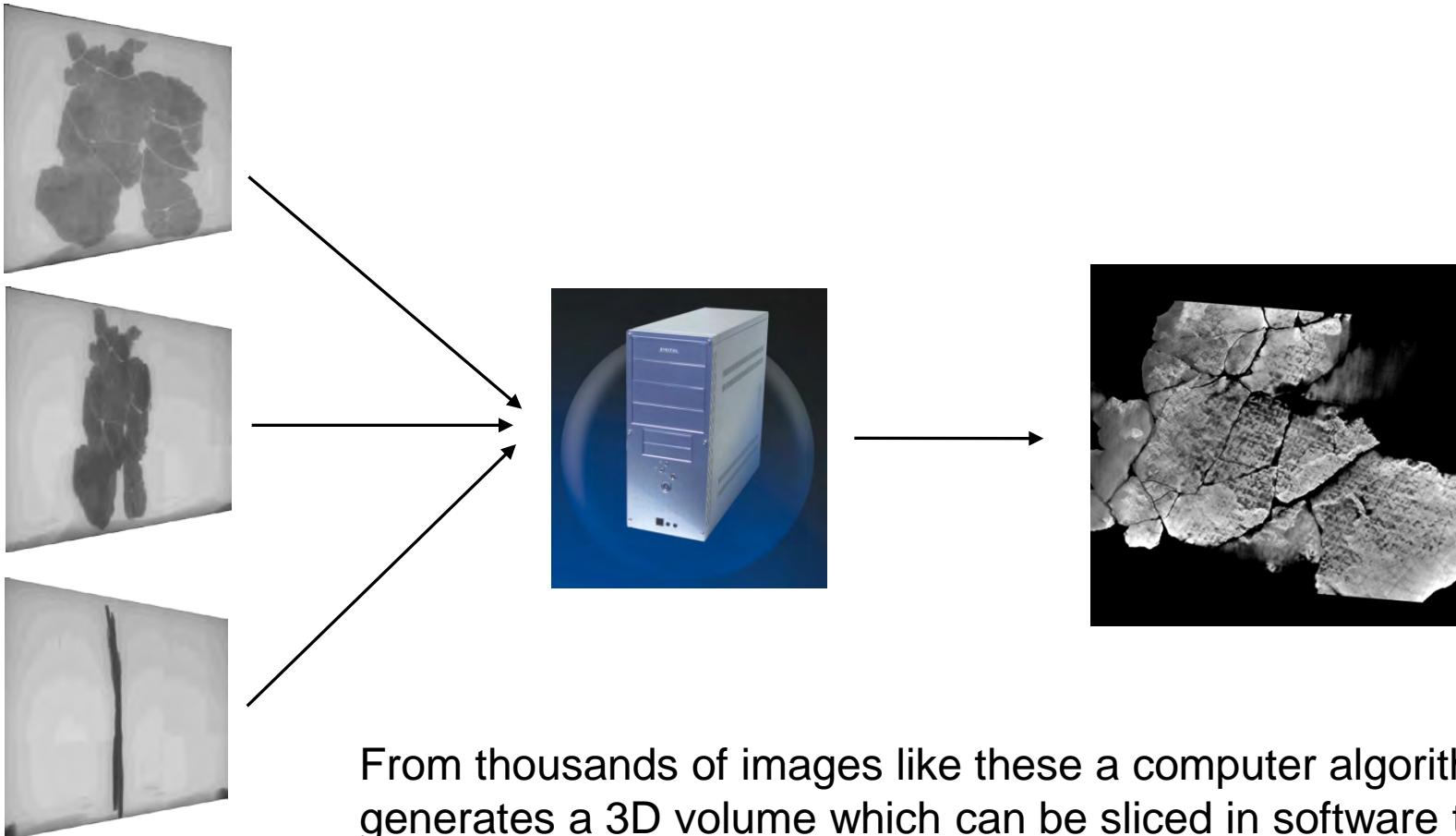
X-ray Computed Tomography

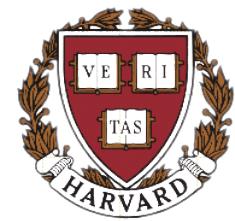
CT requires us to penetrate the object with X-rays from all directions:





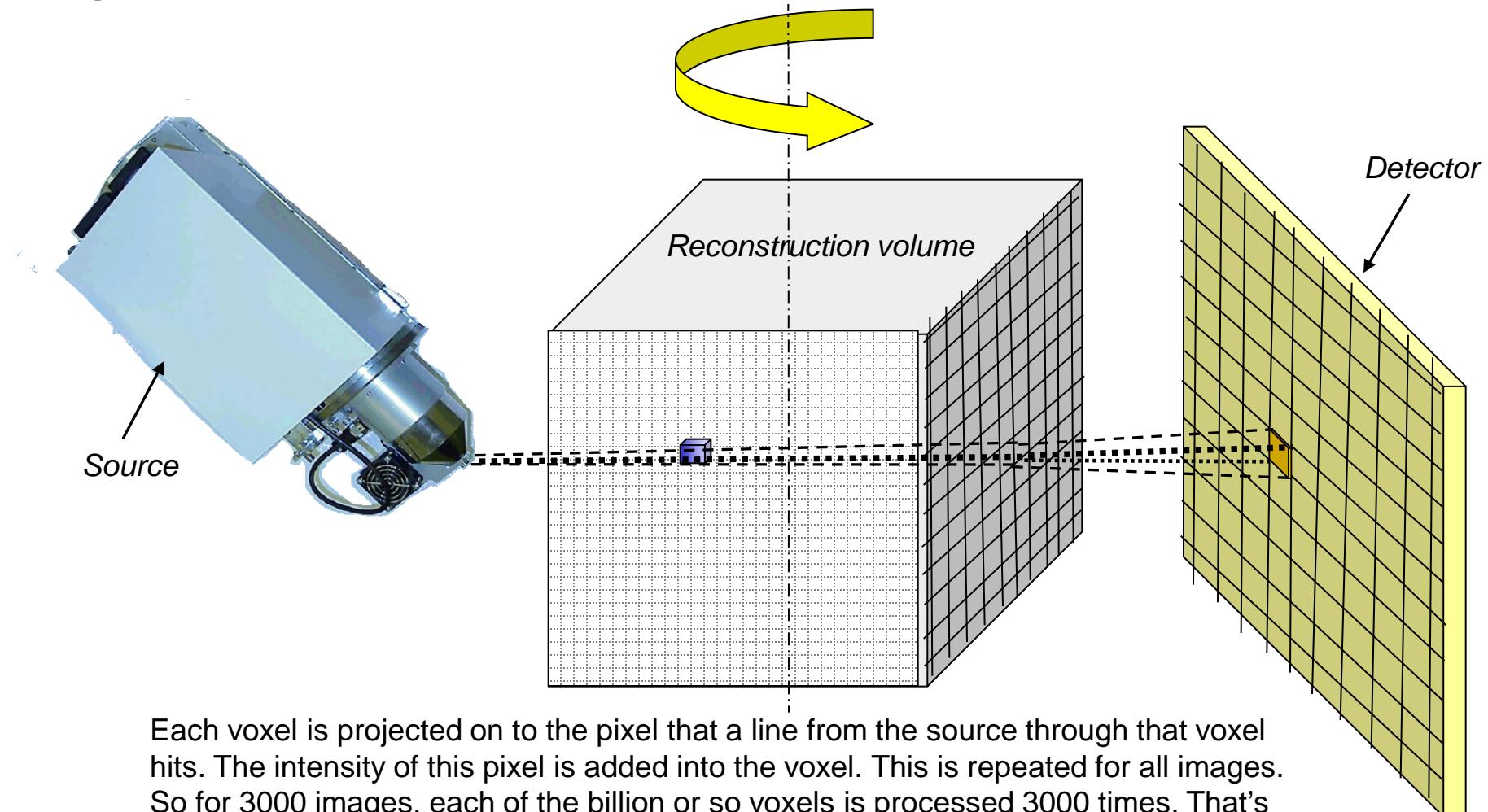
X-ray Computed Tomography



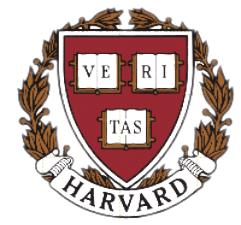


X-ray Computed Tomography

Projecting the volume elements (voxels) onto the picture elements (pixels)

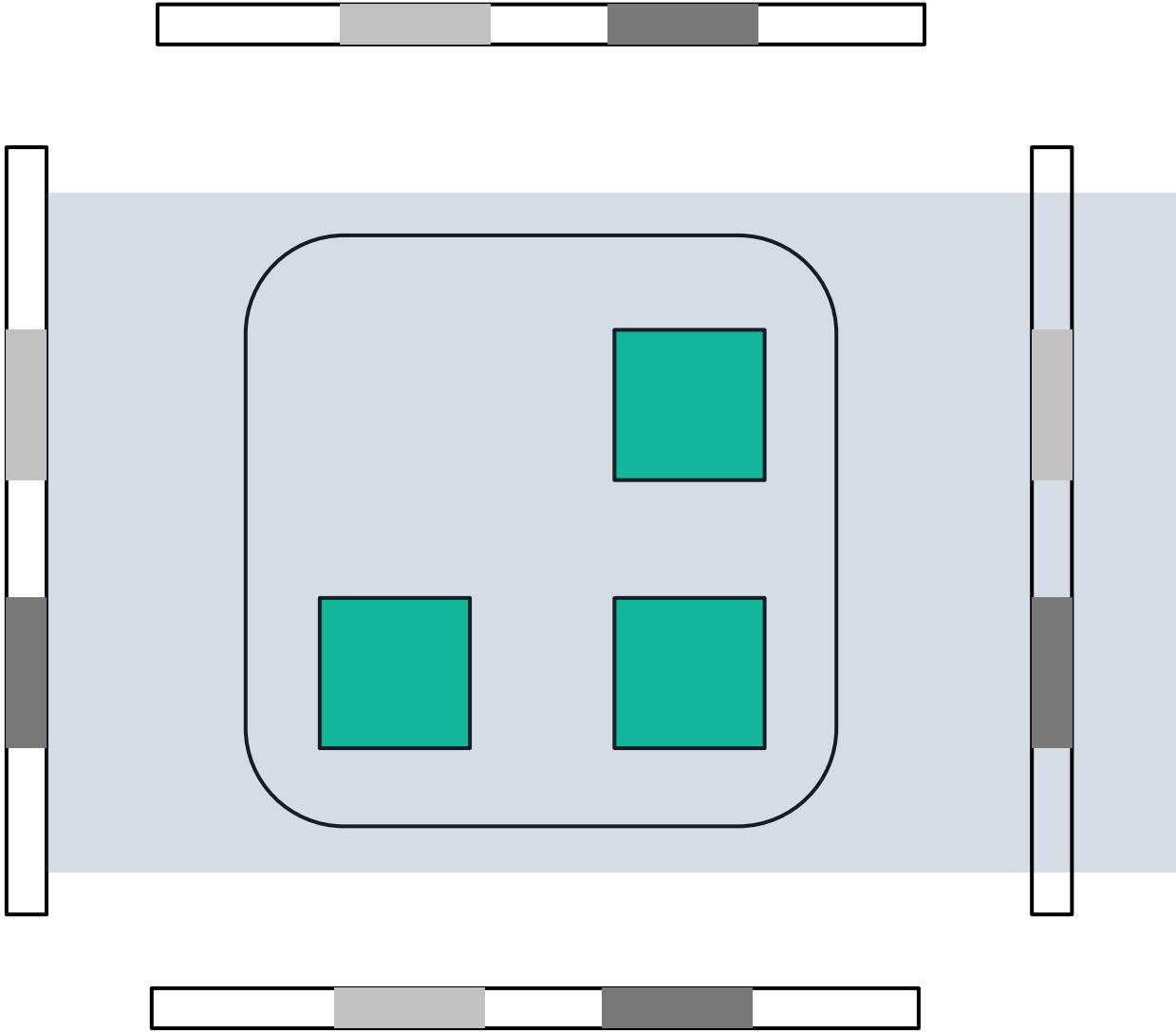


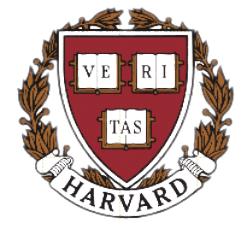
Each voxel is projected on to the pixel that a line from the source through that voxel hits. The intensity of this pixel is added into the voxel. This is repeated for all images. So for 3000 images, each of the billion or so voxels is processed 3000 times. That's why it can take a long time to reconstruct high-resolution CT volumes!



X-ray Computed Tomography

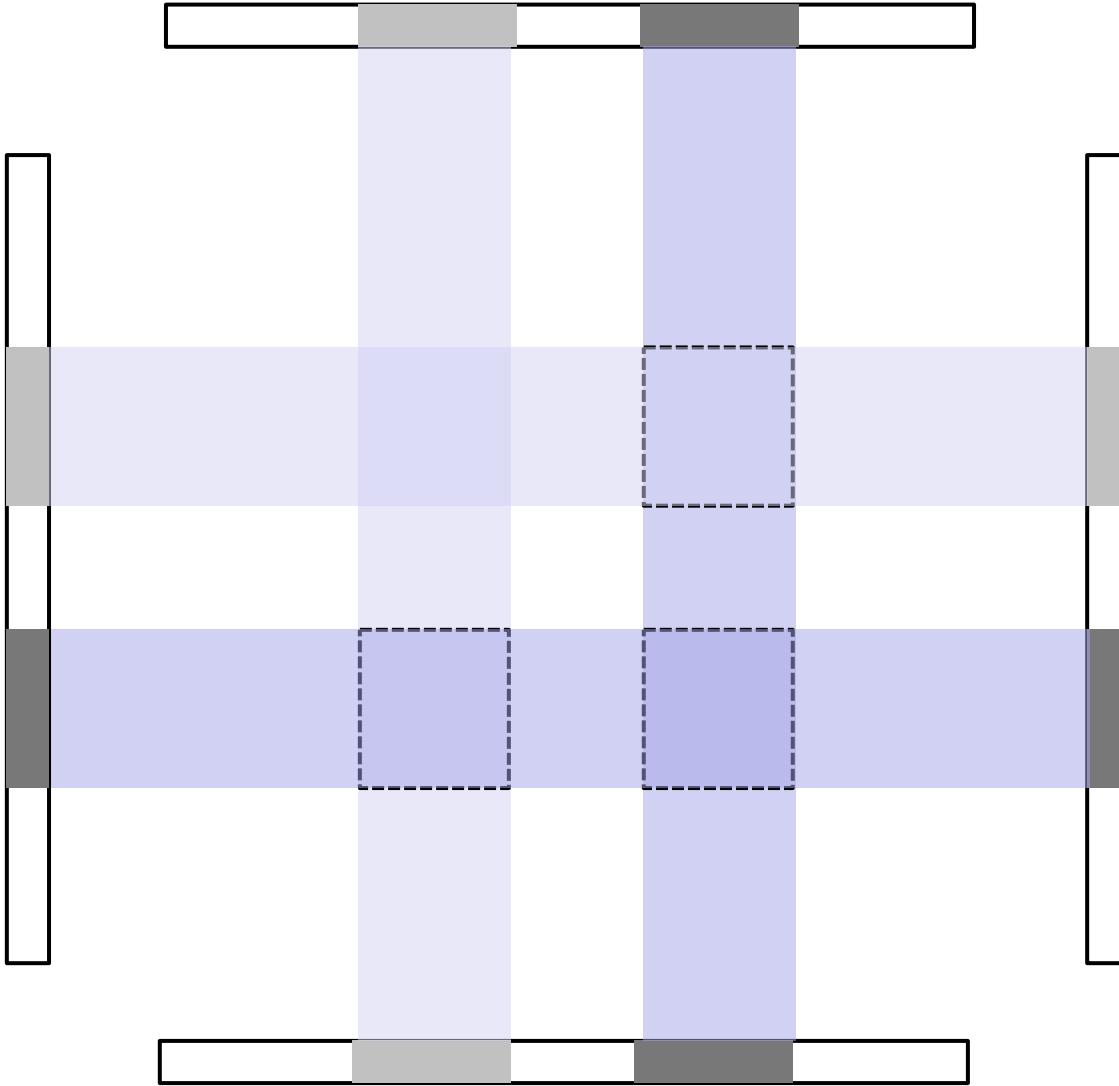
Scanning:
projections

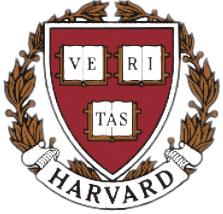




X-ray Computed Tomography

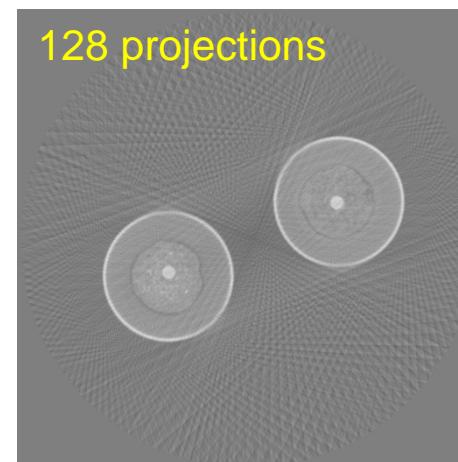
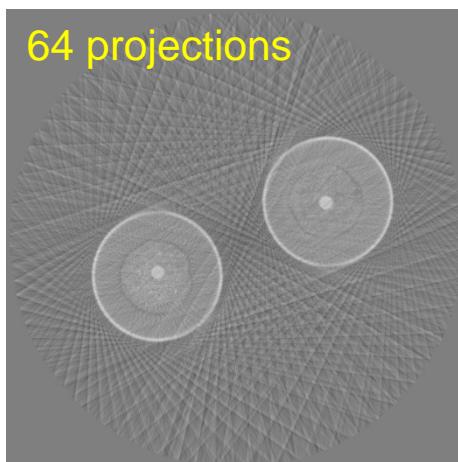
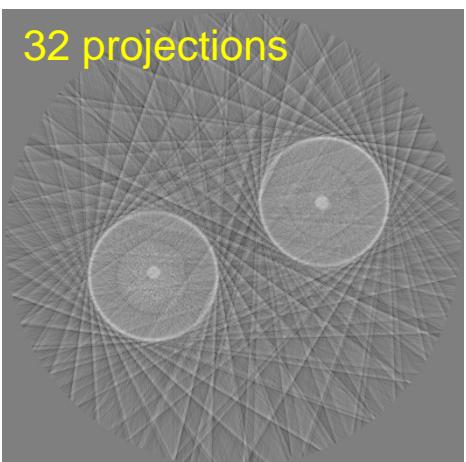
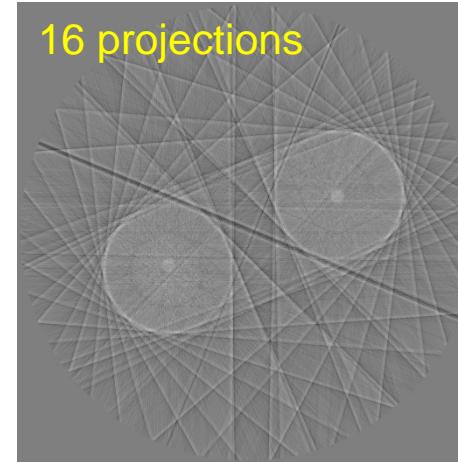
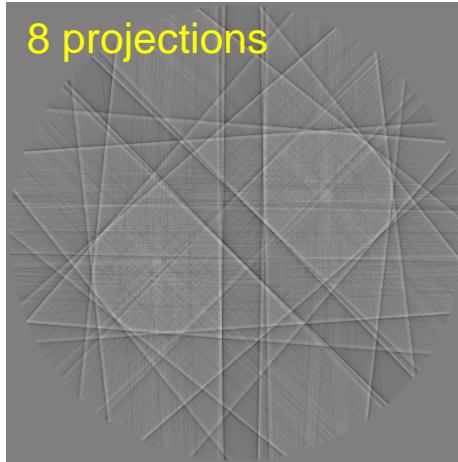
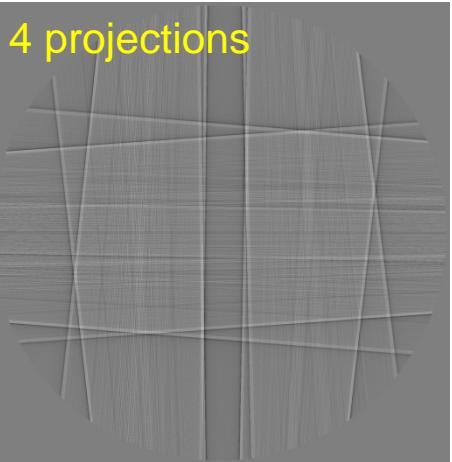
Reconstruction:
backprojections



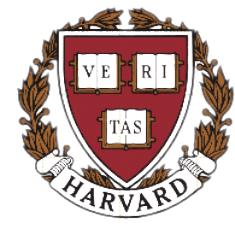


X-ray Computed Tomography

Adding projections from different angles to build a volume:



Horizontal slices through a CT volume of two E90 batteries as projections are added.

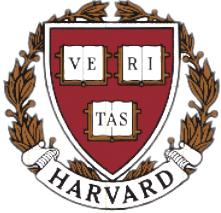


X-ray Computed Tomography

Adding projections from different angles to build a volume:

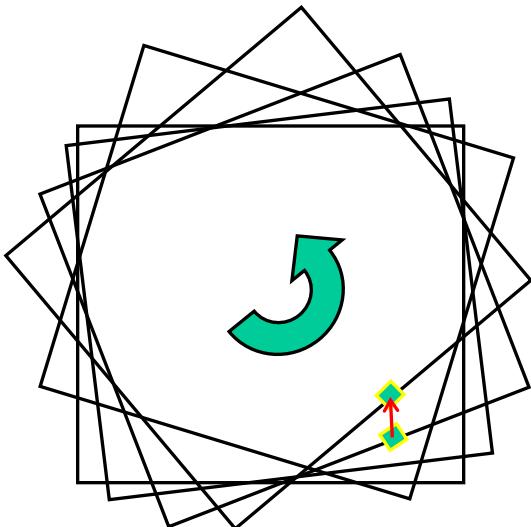


Horizontal slices through a CT volume of two E90 batteries as projections are added.



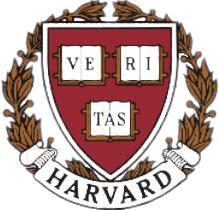
Number of Projections

How many images do we need to collect for a CT scan?



The displacement of an edge pixel from one angle to the next must be no more than the size of one voxel (=3D pixel) in the volume.

For a good quality CT volume we need more than 1000 projection images. To collect these in a reasonable time we used continuous rotation. Typical scans are 25 min (1600 images) to 50 min (3200 images).



Resolution: Contrast

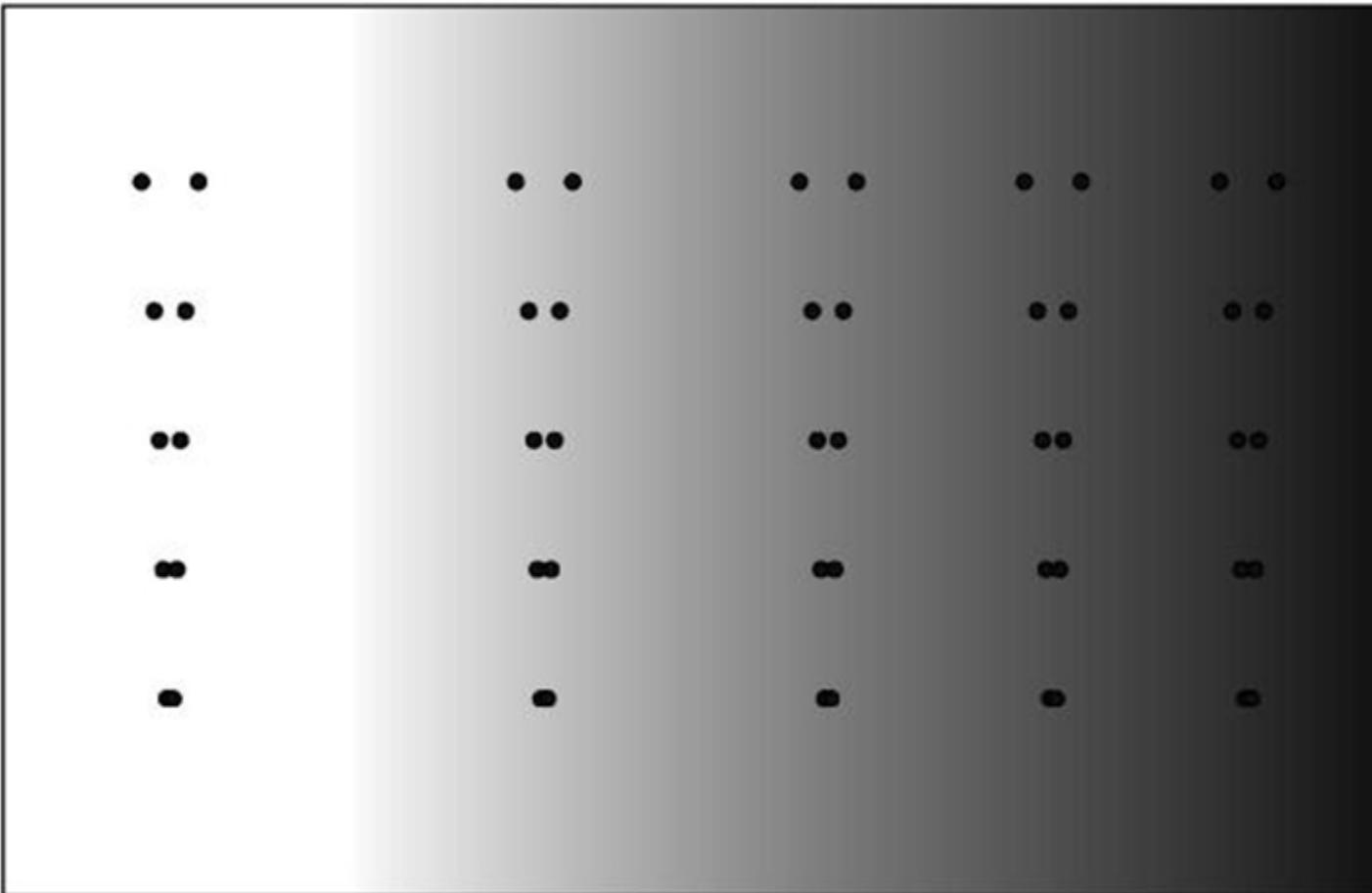


FIGURE 2.6

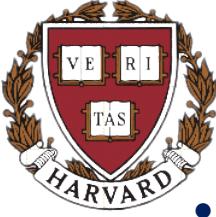
Influence of contrast on resolution of closely spaced features. The 1D gradient of background gray levels makes it more difficult to resolve the pairs of disks the farther to the right one goes.

From: MicroComputed Tomography, Stuart R. Stock



Resolution: Contrast

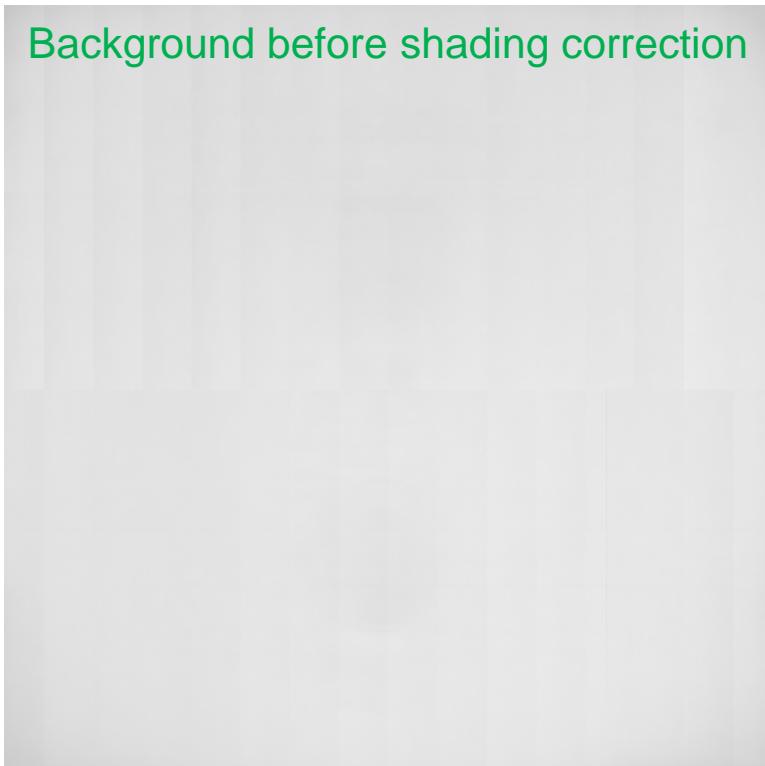
- To get good contrast:
 1. The energy of the electron beam (i.e. the voltage) must be appropriate for the sample: low for “soft” (e.g. biological, polymer) samples and higher for “hard” (e.g. mineral, metal).
 2. The sample must be penetrated by X-rays in all orientations.
 3. The X-ray flux (i.e. the current) must be adjusted to get a background grayscale value close to white.
- Getting good contrast for composite samples made of different materials could be challenging (e.g. a sample made of plastic, silicon, and several different metals).



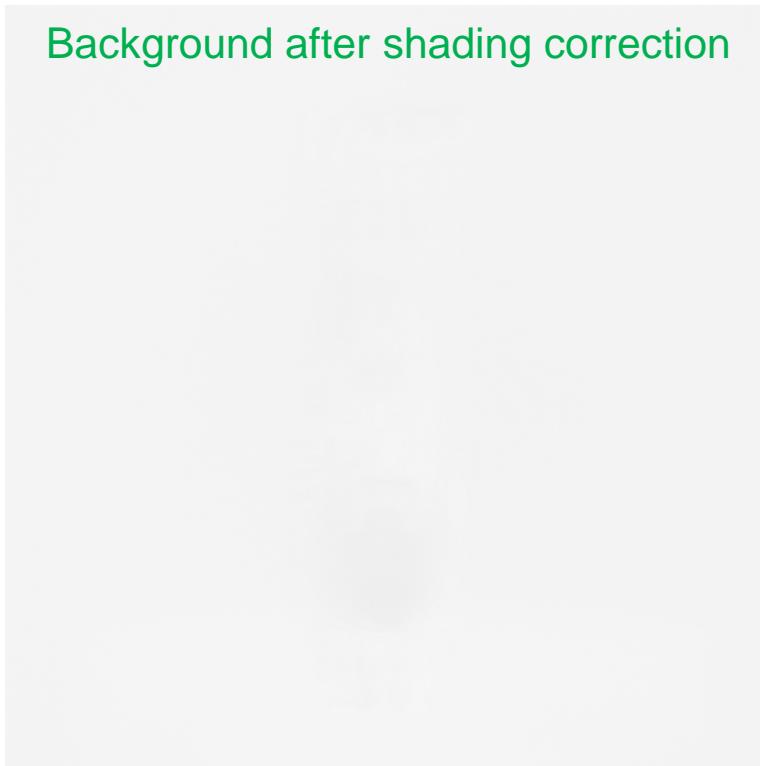
Shading Correction

- A detector calibration done before starting the scan to achieve a uniform background.
- Every single pixel on the detector must be calibrated to display the same grayscale value when exposed to the same X-ray conditions.
- At least two shading correction images, one black (X-rays off) and one white (X-rays on, no sample) must be collected during this step.

Background before shading correction



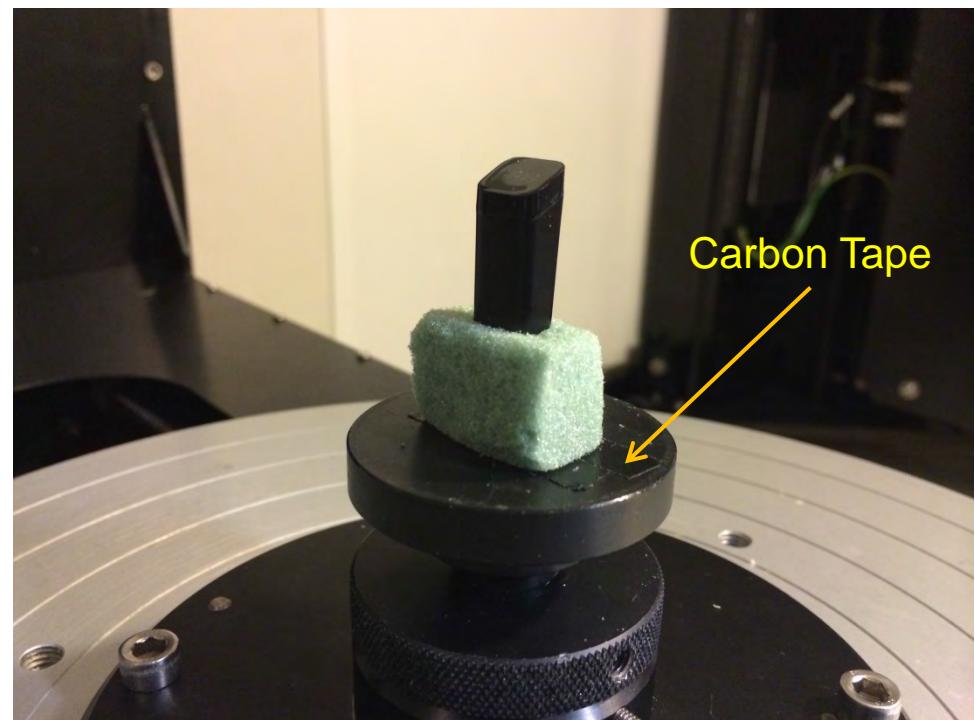
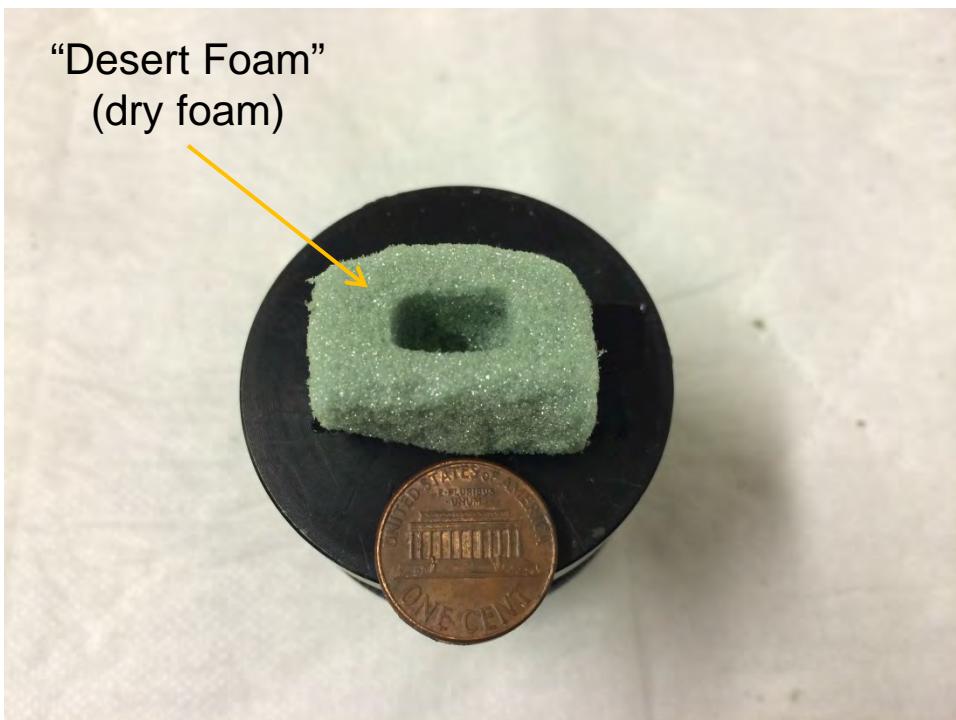
Background after shading correction





Sample Mounting

- Poor sample mounting is the most common culprit for failed scans.
- The sample SHOULD NOT move during the entire scan (except the rotation of the sample stage).
- Especially difficult to achieve with soft, elastic or wet samples.
- Change in temperature inside the chamber of the instrument may cause the sample to move as well.





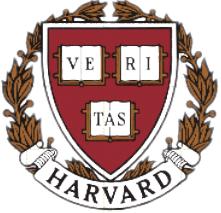
MicroCT in Practice

Artefacts and causes of errors in CT data

Unfortunately, not all CT scans give optimal data.

Some of the following artefacts may be seen:

- Motion artefacts – may appear as double image, blur, or result in failed reconstruction
- Center-of-rotation errors during reconstruction – cause blurring, degraded resolution, or failed reconstruction
- Stage wobble and instability
- Undersampling
- Noise – appears as speckle in the slice images
- Ring artefacts – appear as rings in the axial slice images
- Streak artefacts – from dense structures in the sample
- Scattered radiation – brightens holes and fills in reentrants



MicroCT in Practice

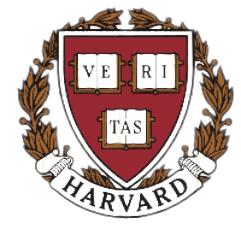
Speed vs Quality = Time vs Noise

The key to good CT data is good signal to noise.

Unfortunately, CT reconstruction exaggerates noise!

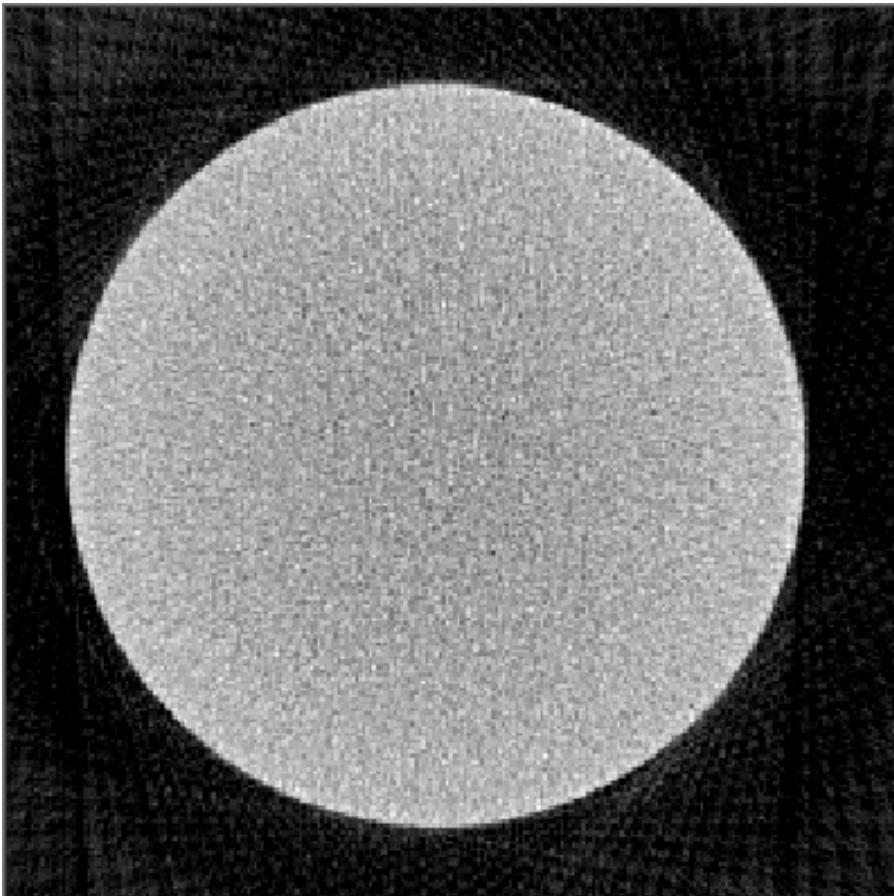
Therefore, we must collect very low-noise projection images.

This is achieved by maximising the detected X-ray dose in each image.

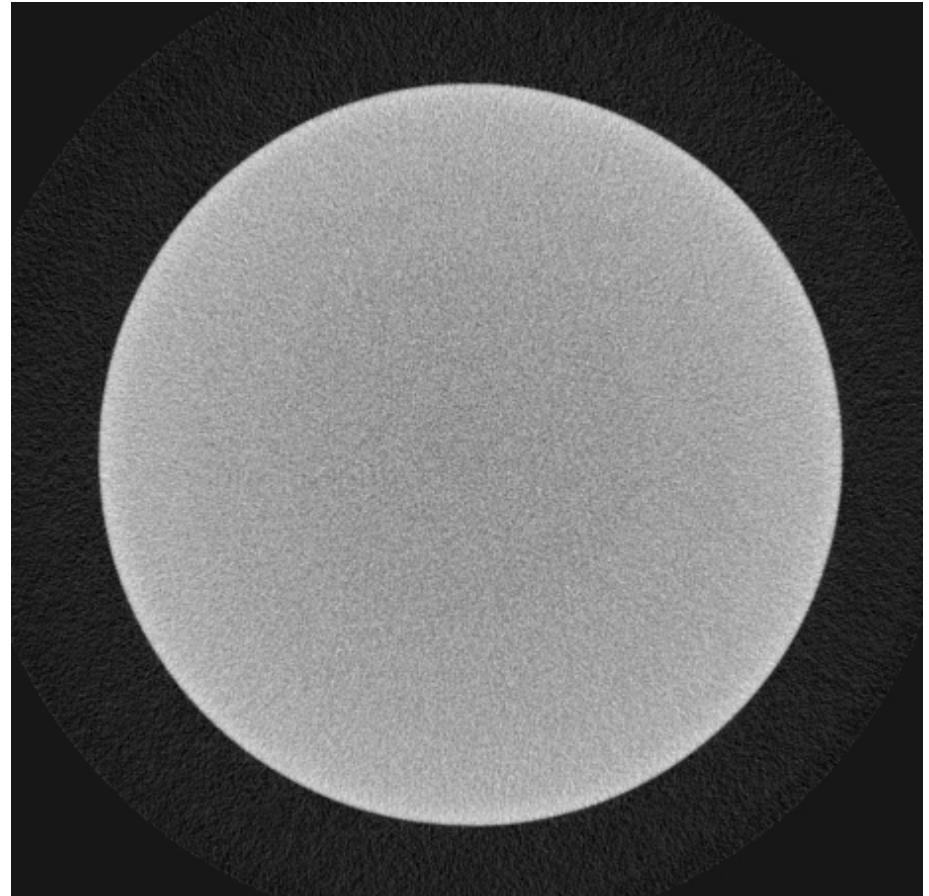


MicroCT in Practice

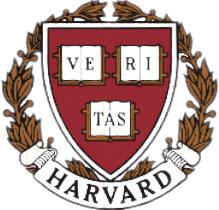
Random Noise



Noisy CT slice



Less noisy CT slice



MicroCT in Practice

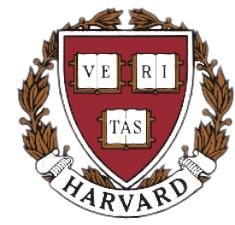
CT quality is proportional to the total number of detected X-rays

The following are measures of the detected X-ray dose:

- Number of projection images (also helps resolution)
- Camera exposure for each image
- Number of frames averaged at each position
- X-ray current (μA)
- Proportion of spectrum passed by filter
- X-ray voltage (kV)

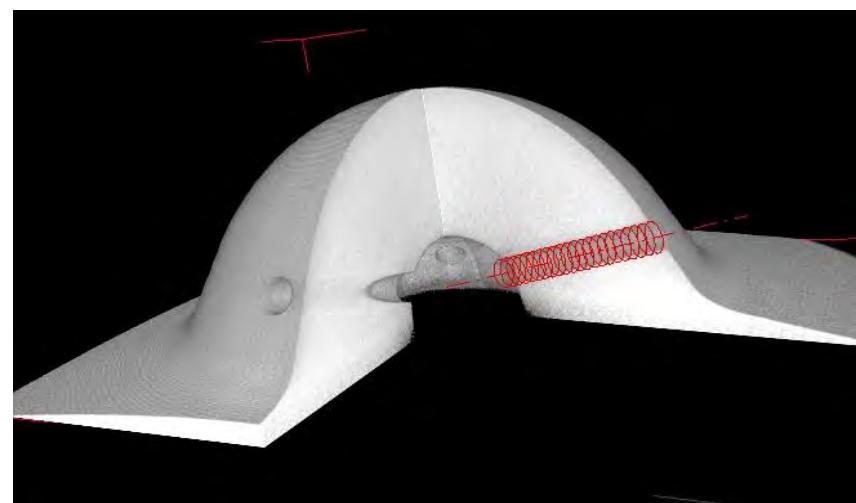
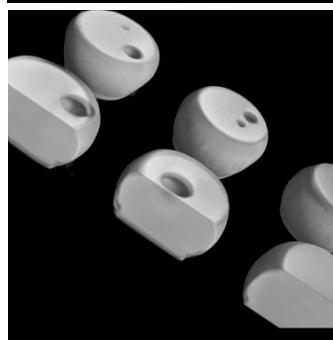
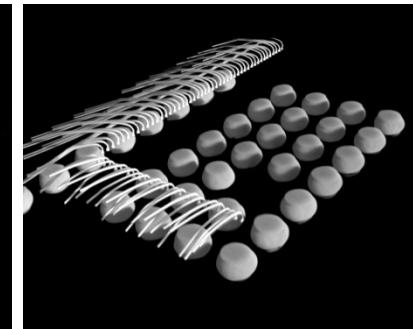
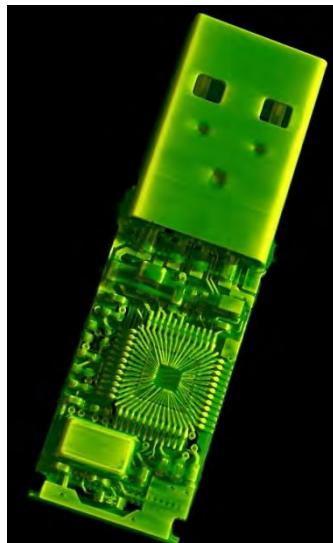
The following do NOT affect the total dose:

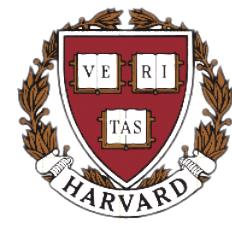
- Detector gain
- Detector binning



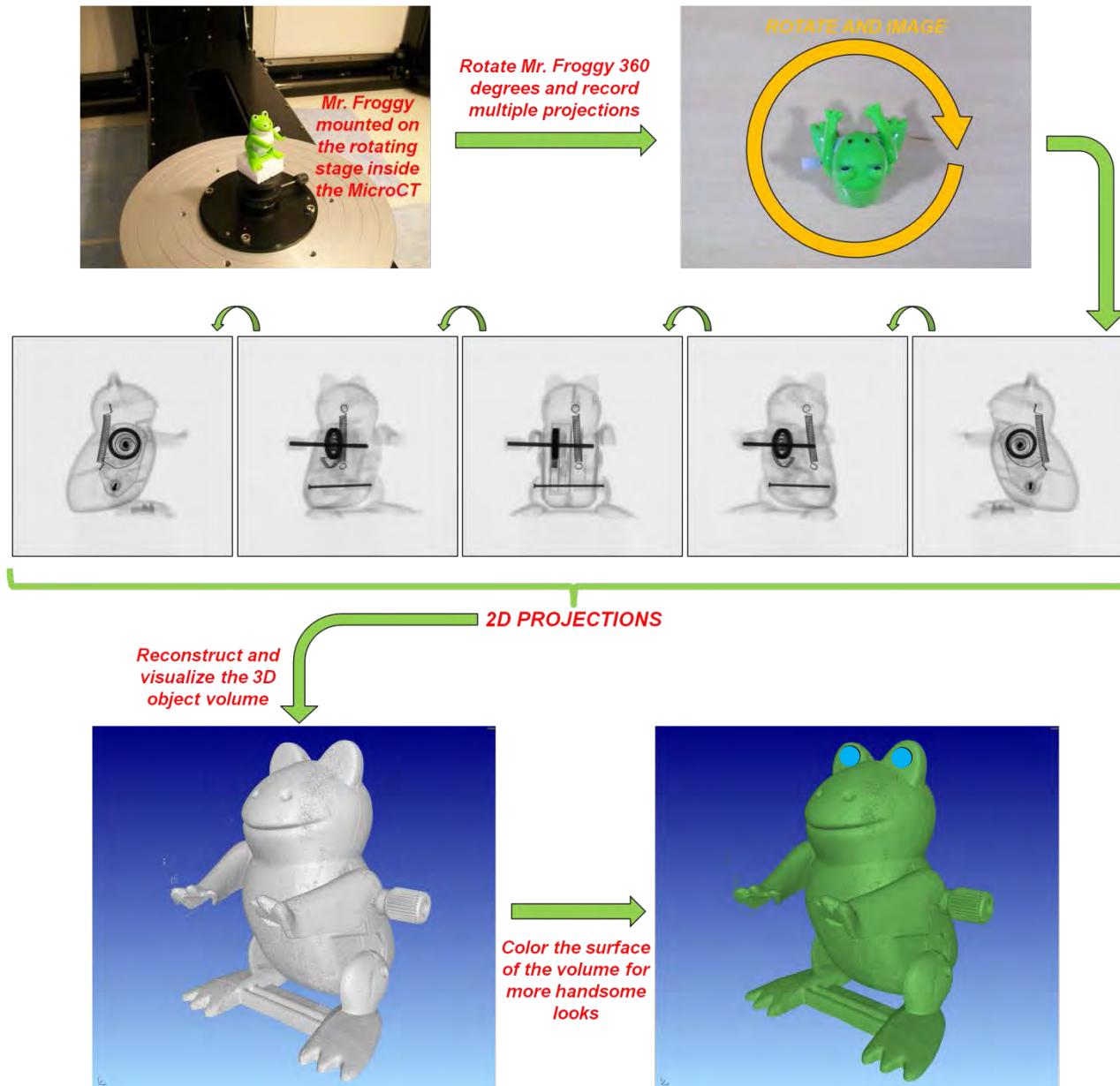
X-ray Computed Tomography

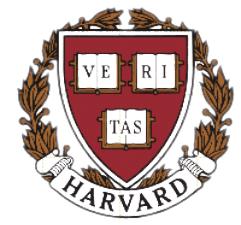
Examples of Computed Tomography





Example: Mr. Froggy





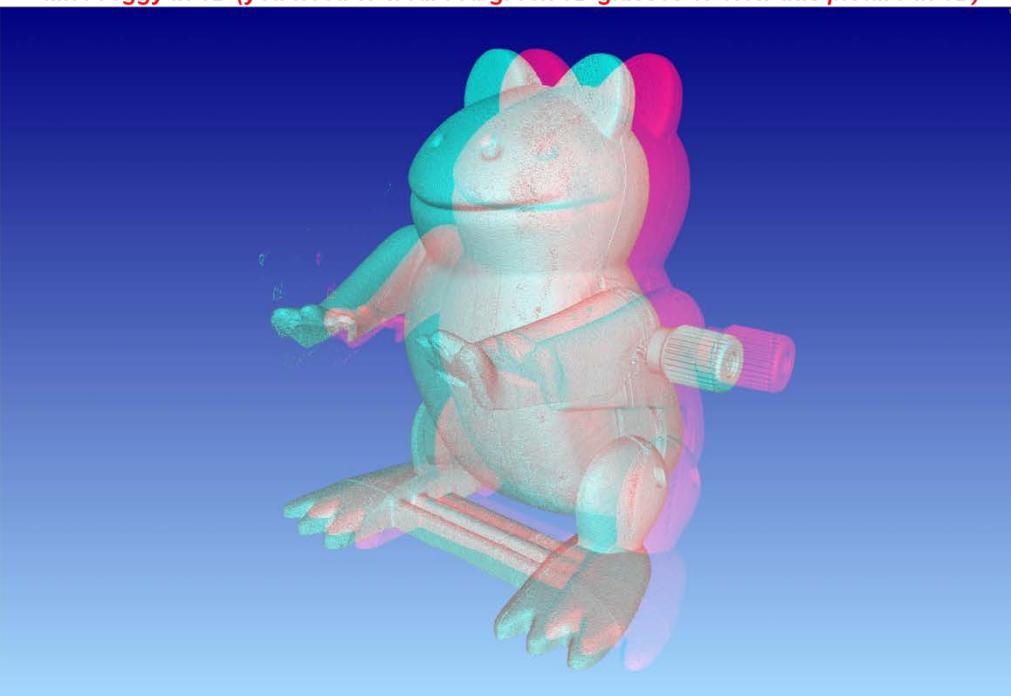
Example: Mr. Froggy

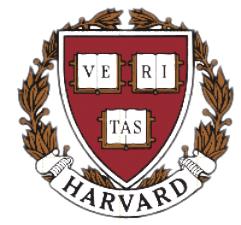


Strip away Mr. Froggy's plastic components

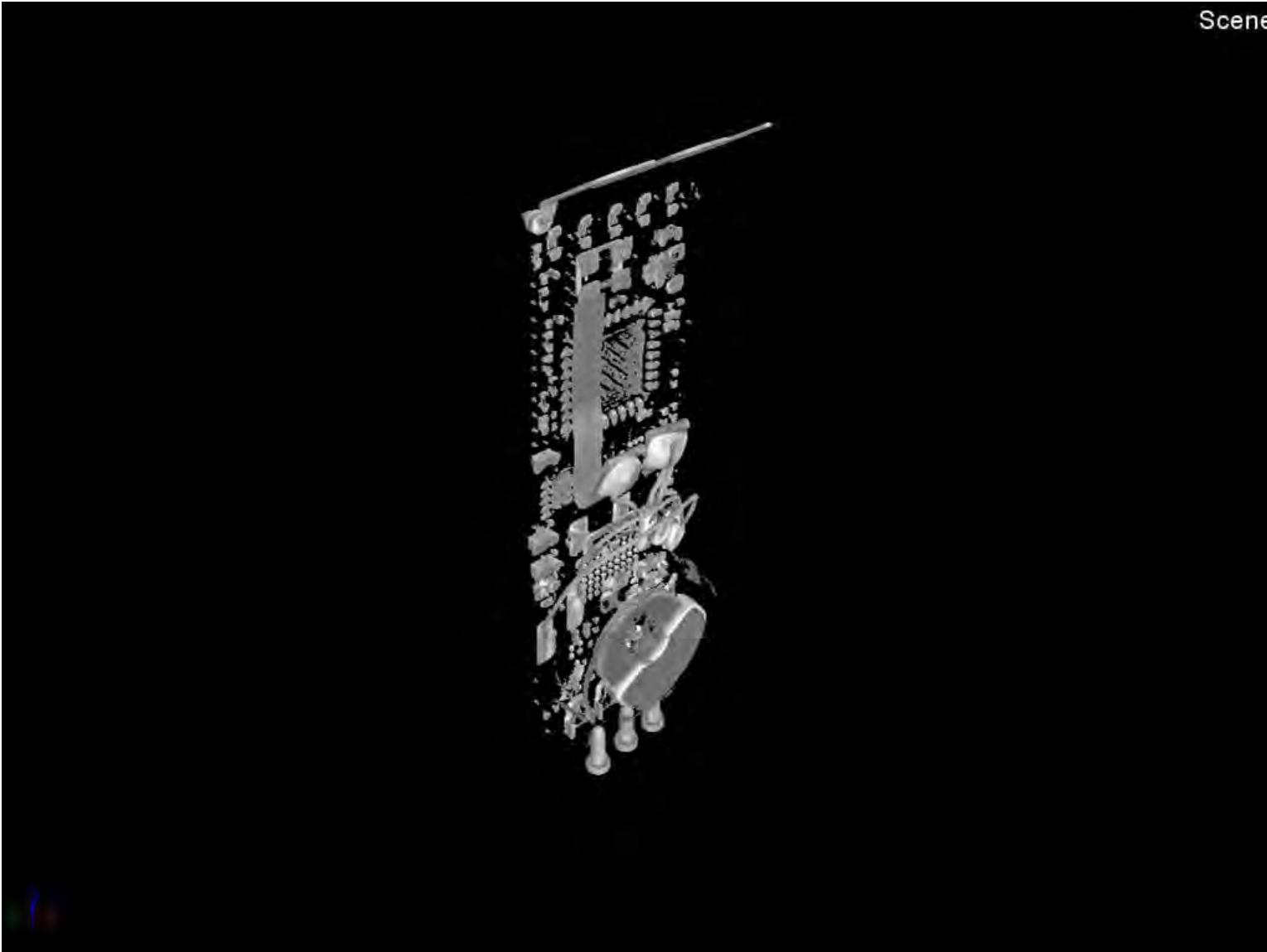


Mr. Froggy in 3D (you need to wear red/green 3D glasses to view this picture in 3D)

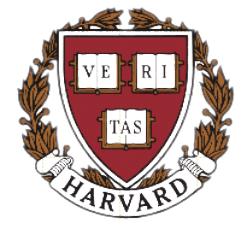




Example: 3D Animation (Fitbit Flex)

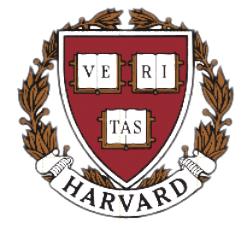


Scene

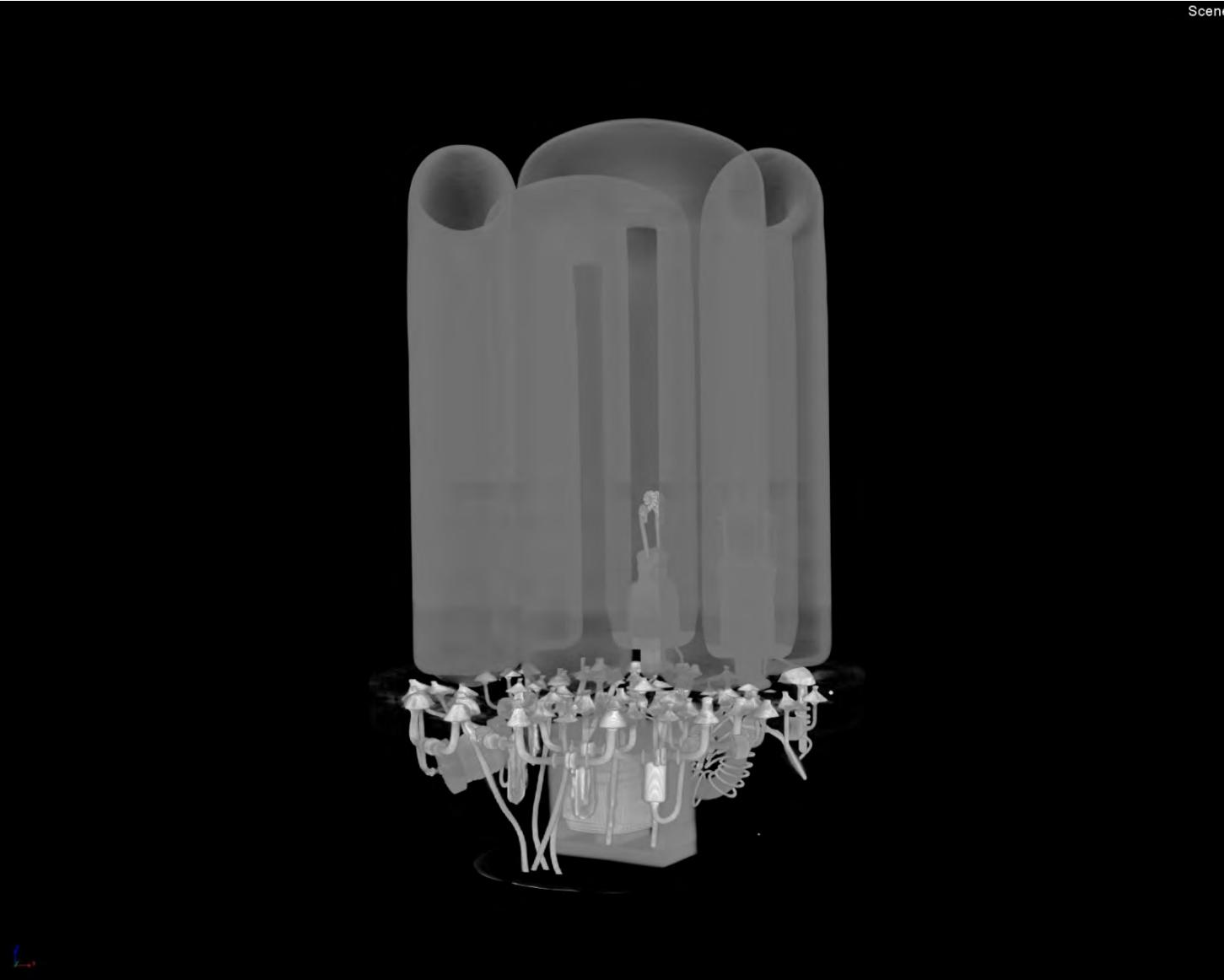


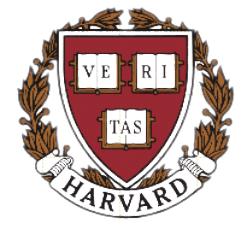
Example: Compact Fluorescent Bulb





Example: Compact Fluorescent Bulb

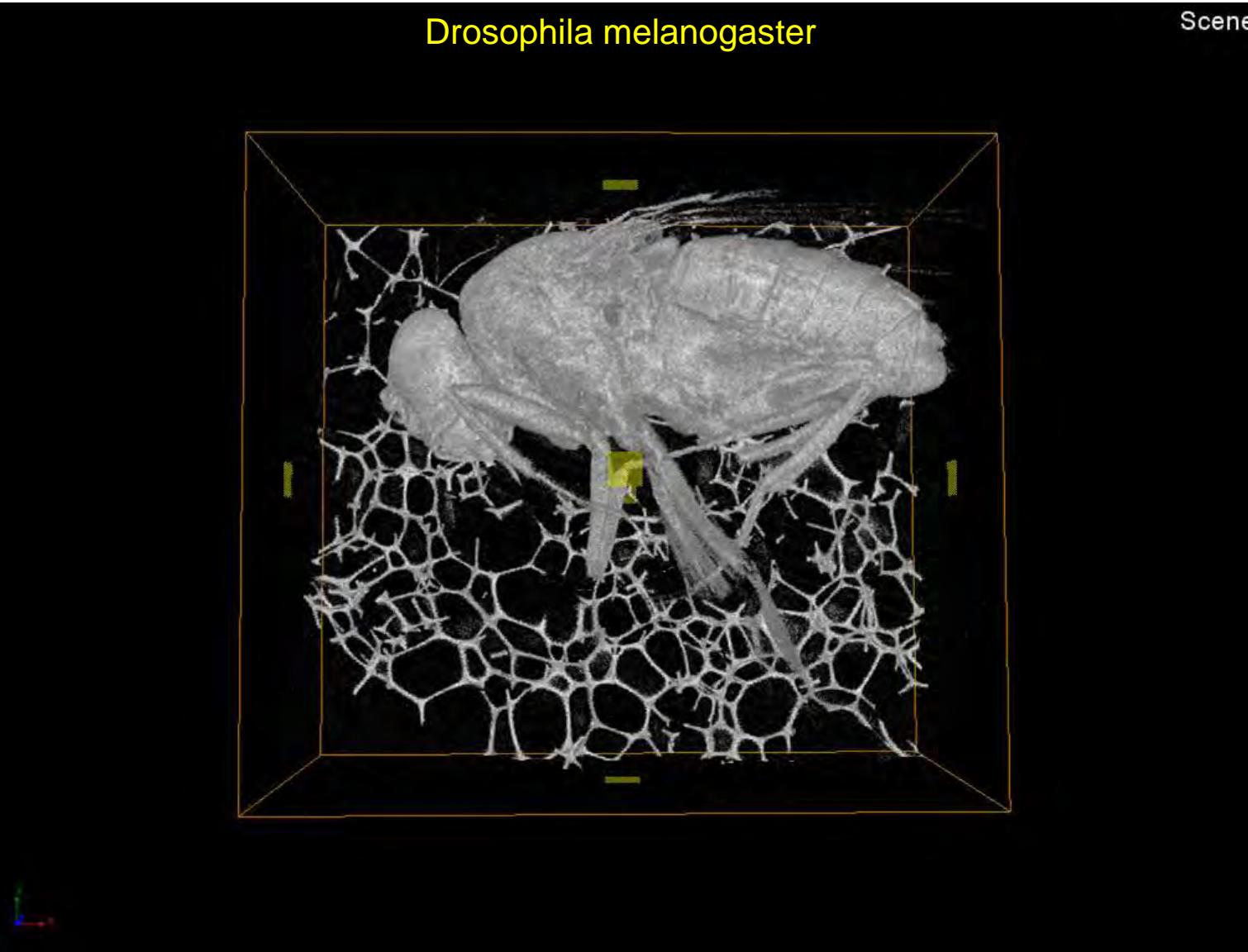


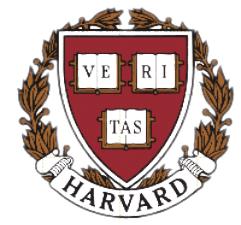


Example: 3D Animation (Fruit Fly)

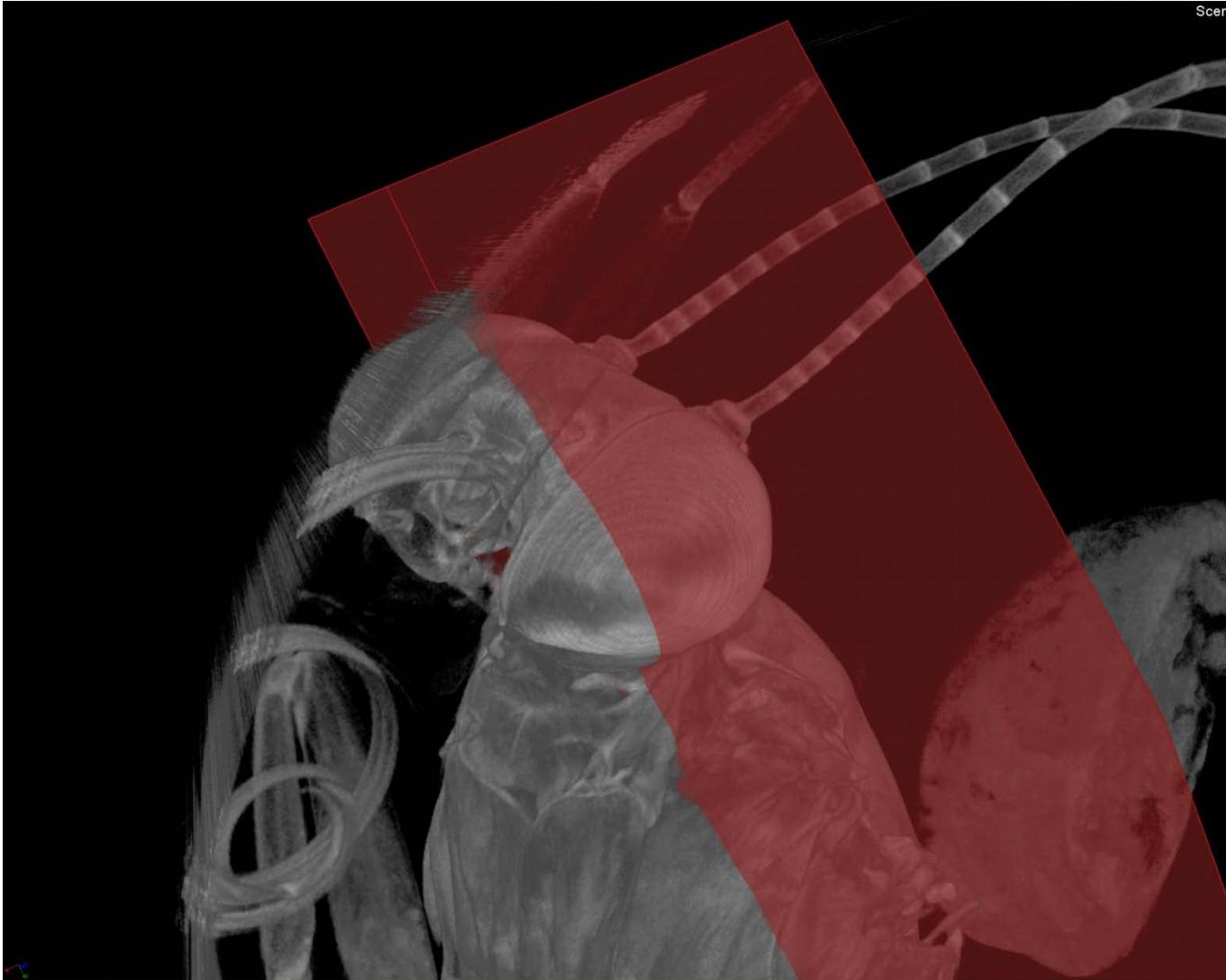
Drosophila melanogaster

Scene





Example: Butterfly Head



(Scan and image by Monica Zugravu @ CNS)

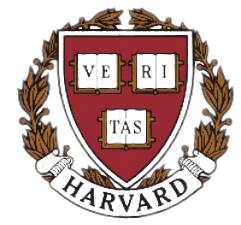


Example: 86M y/o Bird Bones!

Ichthyornis, a.k.a. “fishbird” (with teeth)

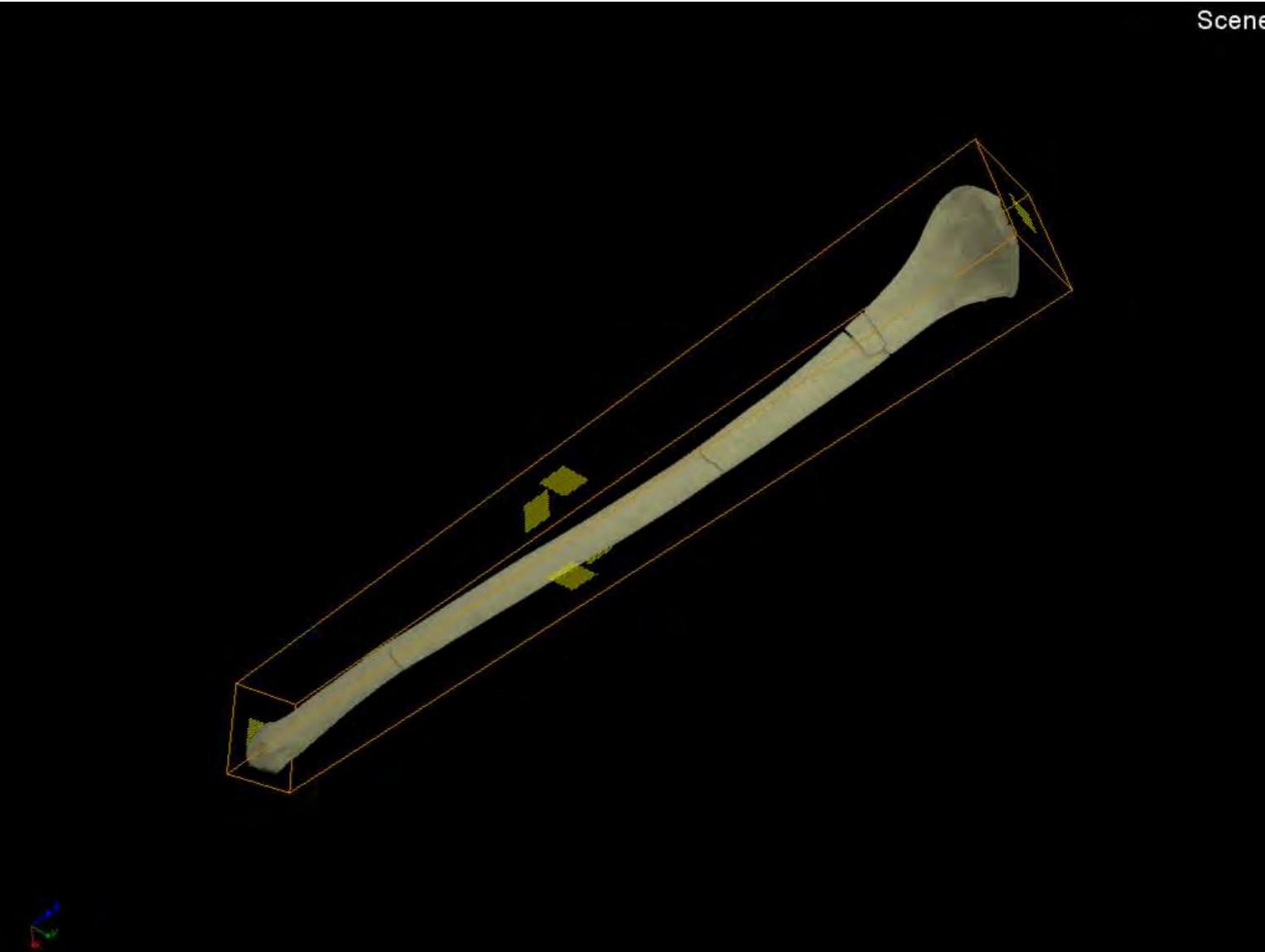


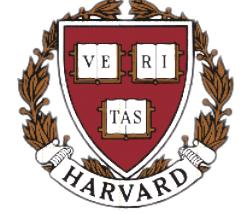
- Scanned by Daniel Field (from Yale) and Prof. Bhart-Anjan Singh Bhullar on our system
- From Yale Peabody Museum of Natural History collection
- Found in marine sediments in Kansas! (Kansas was a sea at that time.)
- Transitional form to modern-day birds: like Homo erectus to humans



Example: 86M y/o Bird Bone

Scene



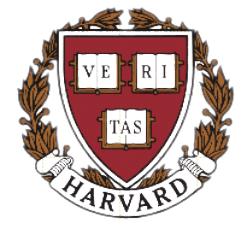


X-ray MicroCT at CNS

LISE G27



- X-Tek HMXST225 system (225kV max)
- Three reconstruction workstations
- Software:
 - InspectX: X-ray imaging and CT acquisition
 - CT Pro 3D: volume reconstruction
 - VG Studio MAX 2.2: 3D volume visualization, rendering and analysis
 - Amira: 3D volume visualization, rendering and analysis



Questions? Comments?

fkosar@cns.fas.harvard.edu



Interested? Sign up for X-ray MicroCT
training on CNS website!