This CAT Can See through You

Paul S. Wang, Sofpower.com

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We often say that *computational thinking* (CT) is important in the digital age and CT can even save lives. Here we talk about a **different CT**, *Computed Tomography*, whose sole purpose is to see inside your body as a medical tool. And this CT may very well save your life.

In the beginning, the breakthrough technology was called *Computer Assisted Tomography* (CAT) then later it became *Computed Axial Tomography.* Now, it has lost the 'A' and become simply CT–*Computed Tomography.*

The invention, development, and evolution of CT is a fascinating story of discovery, persistence and incremental refinement as well as a perfect example of the **quantity to quality transformation**.

In this article, we will describe CT, how it got started, evolved, and became the indispensable equipment in modern hospitals. We will also explain how CT works and the critical role computing plays in it.

An understanding of CT is important for everyone who may need it for health care and especially for computational thinkers as an ingenious application of computing that benefits everyone.

Please note: In the reminder of this article the term CT stands for computed tomography unless otherwise specified in which case it means *computational thinking.*

What is CT?

CT stands for *Computed Tomography.* According to *Merriam-Webster* dictionary, the word '*tomography*' means

> *a method of producing a three-dimensional image of the internal structures of a solid object (such as the human body or the earth)*

by the observation and recording of the differences in the effects on the passage of waves of energy impinging on those structures.

Often, tomography combines a number of cross-sectional images of the object to build a three-dimensional view. These days, CT almost always refers to a non-invasive diagnostic medical procedure that uses X-ray around a patient to obtain a three-dimensional image of a particular part of the patient's anatomy.

X-rays are a form of invisible light with very short wavelength and high energy photons that can penetrate many materials including the human body. When an X-ray bean passes through an object, such as a human body, its energy is absorbed or *attenuated* in varying degrees depending on the material and its density. Bones attenuate X-rays much more than soft tissues. Such variations result in different brightness/darkness in the resulting X-ray image.

Figure 1: Plain X-rays of the Head

Figure 1 shows two X-rays of the human head, a front and a side view. Such *plain X-rays* are ideal for spotting fractures, dislocations, tooth cavity/decay and so on. Because a plain X-ray image is taken from one direction or angle, much interior details can become obscured. Thus, it won't show subtle bone injuries, soft tissue damages or inflammation. Note that in the plain head X-rays (Figure 1) the interior of the head (the brain) is obscured by the skull. CT scan can solve this and other problems of plain X-rays.

A CT scan sends X-ray beans from multiple angles through the body to produce much more detailed images of body interiors than plain X-rays as can be seen in Figure 2. The 2D images, known as *slices*, are created by

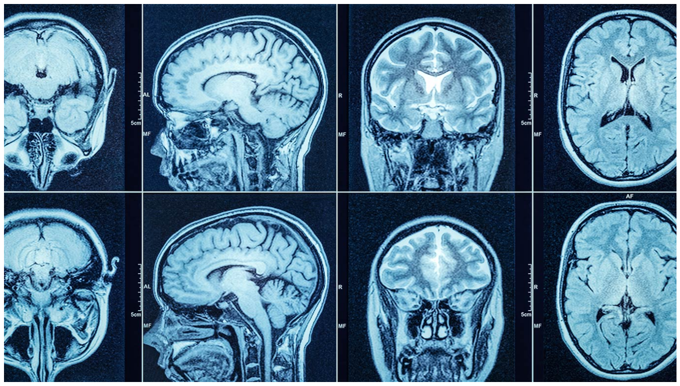

Figure 2: Head CT Slice Images

computers. They allow radiologists and doctors to see the brain inside the skull. CT scans can spot blood clots, tumors, subtle bone fractures, organ injuries, and so on. CT scans take slightly longer than plain X-rays but are still fast, taking about a minute. Thus, CT is also ideal for emergency situations.

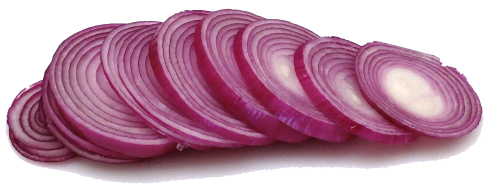

Figure 3: Slices Can Make the Whole Onion

In CT, the 2D slices (Figure 3) can also be combined using computer image processing algorithms to create a comprehensive 3D representation of, for example, the head's internal structures. This 3D reconstruction can be displayed on computer screens, allowing medical professionals to navigate through the 3D image, rotate it, and examine structures from different angles and viewpoints (Figure 4).

While the 3D reconstruction provides a more intuitive visualization of the overall anatomy, the primary output of a CT scan is still a series of 2D slices. These slices are often used for detailed analysis and diagnosis, while the 3D reconstruction is useful for surgical planning, teaching, and conveying complex spatial relationships.

Figure 4: Head CT 3D Image

The Invention of CT

The invention is a fascinating story of cooperation of unlikely heroes, unhindered by conventional thinking, breaking out of the box.

Ideas and methods related to *tomography* traced back to the early 1900s. With the availability of computers, the concept of **computed tomography** was first introduced in the early 1960s. Later, the invention of the CT scan was credited to British engineer Godfrey Hounsfield and South African-born physicist Allan Cormack. In 1972, they jointly received the Nobel Prize in Physiology or Medicine for their work in developing the technique.

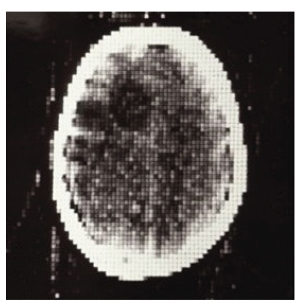

Figure 5: The First Clinical CT Scan, with brain tumor visible as darker blob

Early CT scanners were quite different from the sophisticated systems we have today. The first CT scan (October 1, 1971) took several hours to acquire a single slice, and the image quality was limited (Figure 5) to put it mildly. However, over the years, advancements in methods, technology and computing have revolutionized the field.

According to a *Journal of Medical Imaging* article (Schulz et el. 2021):

> *Godfrey N. Hounsfield joined Electric and Musical Industries (EMI) in 1949 when he was 30. His only formal training was an Associates Certificate from the Faraday House. … He had a passion for understanding basic principles of technologies and worked on radar during the wartime effort prior to joining EMI.*

And working in a research arm of EMI, Hounsfield (Figure 6)

> *asked himself the general question: could the unknown contents of a box be calculated by taking "readings" through the box? As it happened, in the late summer of 1967, during a vacation trip he met a physician who bemoaned the drawbacks of conventional radiography. This may have been his first introduction to human anatomy as an example of the problem of "reading through a box."*

Figure 6: Wanting to See Inside a Closed Box

> *He pondered whether a system could theoretically recognize text in a closed book, page by page, "by shining a bright light across each page from various angles and measure what came out the other end." He had simplified the volumetric "book-box" problem*

> *to a two-dimensional problem by breaking it down into a series of parallel slices. He believed that "given enough information you could calculate what was written on the page".*

While "reading the pages of a closed book" provided the conceptual breakthrough, exactly how to do it was the main challenge. It so happened that Allan M. Cormack had a physics background and was interested in the attenuation of X-ray through an inhomogeneous media. Cormack made measurements of a simple dummy composed of aluminum and Lucite and produced plots of attenuation coefficients along profiles through the object. The measurements were made using X-ray along parallel lines from different angles with the aid of a computer. This was arguably the first experimental demonstration of *computer assisted tomography* (CAT), The work warranted subsequent recognition in sharing of the Nobel Prize with Hounsfield.

How Does CT Work?

CT uses X-rays and computer processing to create detailed cross-sectional images of the body. It provides visualization of internal structures, such as organs, bones, blood vessels, and soft tissues, in multiple planes without surgery or invasive procedures. Here's how CT works:

1. **X-ray Source and Detectors**: A CT scanner consists of an X-ray source and an array of X-ray detectors. The X-ray source emits focused X-ray beam(s), and the detector(s), positioned opposite the source, will receive the beam(s) after passing through the patient. The X-ray tube and the detector(s) rotate around the patient, acquiring multiple X-ray projections from different angles.

2. **Data Acquisition**: During the CT scan, the X-ray tube and detector array typically move in a circular path around the patient. The X-ray beams pass through the body and are attenuated (absorbed or scattered) by the different tissues they encounter.

3. **Raw Data Collection**: The detectors measure the intensity of the X-ray beams emerging from the patient, generating a set of raw data points (of beam intensities after attenuation) for each projection angle. These raw data values are used to compute an image slice.

4. **Image Reconstruction**: The raw data are then processed by a computer to construct one or more image slices. This process involves applying mathematical algorithms, such as filtered back projection or iterative reconstruction, to convert the raw data into cross-sectional images.

5. **Cross-Sectional Images**: The reconstructed images represent slices of the body in the axial plane (transverse or horizontal slices). These cross-sectional images show the internal structures and organs in detail, allowing physicians to examine the body layer by layer.

6. **3D Images**: With the help of advanced computer software, the data can also be used to create 3D images that can provide a more comprehensive view of complex structures and aid in surgical planning.

Evolution of CT Technologies

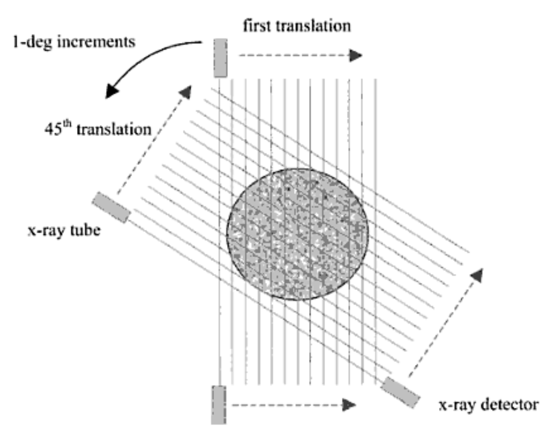

Figure 7: First Generation CT

The *1st generation CT* (1970s) used a single detector and single X-ray source. The X-ray tube and detector assembly translates together linearly, repeating the translation at multiple angles (Figure 7 and Figure 8 a). The scan was slow and the image quality was low.

The *2nd generation CT* (late 1970s) used a fan-shaped X-ray beam and multiple detectors opposite the X-ray source. The *3rd generation CT* (1980s) used curved array of detectors that rotated in sync with the X-ray source around the patient (Figure 8 c).

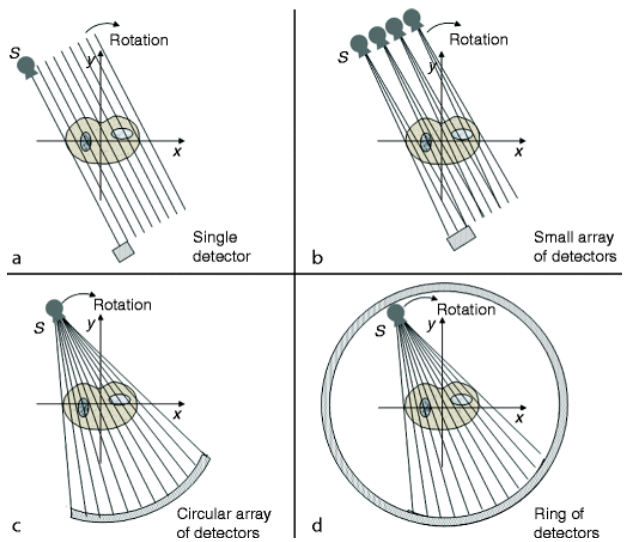

Figure 8: CT Generation 1–4

The *4th generation CT* (1980s-1990s) encircled the patient with a full-circle stationary ring of detectors to receive projections from a rotating X-ray tube around the patient (Figure 8 d). The *5th generation CT* (mid-1990s to early 2000s) used an electron beam magnetically steered to hit detectors surrounding the patient eliminating mechanical moving parts.

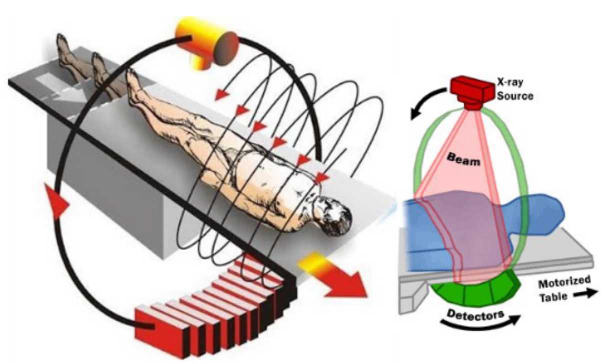

Figure 9: CT Generation 6

The *6th generation CT* (late 1990s to early 2000s) used nonstop X-ray tube+detector rotations (through multiple 360-degree turns) while the patient table moved in a constant speed through the gantry, resulting in fast spiral data acquisition (Figure 9).

Other improvements continued including AI techniques for evaluating CT scans and support for radiologists. CT has come a long way since its invention. The CT scanner improved in speed, efficiency, radiation dosage, and image resolution. Modern CT scan can tolerate limited patient movements and can even image a beating heart (Figure 10).

Figure 10: Modern CT Scanner, patient entering gantry

Importance of Computers for CT

It goes without saying that computing is central to CT technologies. As computers become smaller, faster, and more powerful so do CT scanners.

Modern CT scanners rely on a combination of individual computers within the scanner itself, as well as networks of computers for data processing, storage, and advanced image analysis. This complex interplay of computing components ensures that CT scans are acquired, processed, and interpreted accurately and efficiently.

The speed of data collection enables faster scans. The ability to process vast amounts of data makes advanced reconstruction of the image slices run faster and more accurately resulting in better resolutions in the 2-D and 3D images created.

Specific application areas of computers in CT include:

- Scanner control and data acquisition
- Data processing for image reconstruction

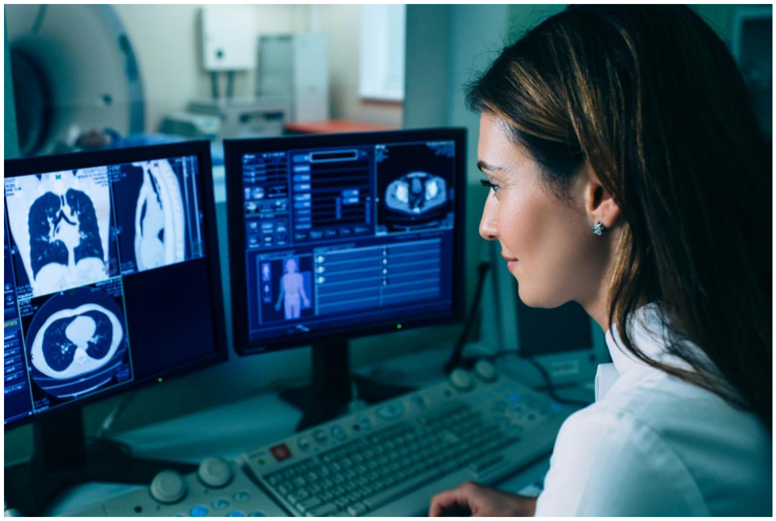

Figure 11: Doctor Viewing CT Images

- Image processing and enhancement
- Image presentation, review and analysis (Figure 11)
- Image/data storage and archiving
- Remote access for telemedicine
- Incorporating AI techniques

Applications and Impact of CT

The impact of CT on medicine and healthcare has been profound, revolutionizing the way medical professionals diagnose, treat, and monitor a wide range of conditions. Here are some of the significant ways in which CT has transformed the field of medicine:

1. *Accurate diagnosis*: Enabling accurate diagnosis of a variety of conditions, including fractures, tumors, infections, vascular diseases, and more.

2. *Early detection*: Allowing for timely interventions and better treatment outcomes.

3. *Guidance for Procedures*: Guiding surgical and minimally invasive procedures, such as biopsies, tissue removal, and placement of medical devices like stents and catheters.

4. *Cancer/tumor management*: Helping cancer diagnosis, staging, treatment planning, and monitoring.

5. *Trauma Assessment*: Crucial in evaluating traumatic injuries, especially head, spine, and musculoskeletal injuries, aiding rapid and accurate assessment and treatment decisions.

6. *Vascular imaging*: Providing detailed images of blood vessels, aiding in the diagnosis of conditions such as aneurysms, blockages, and vascular malformations.

7. *Neurological Evaluation*: Brain CT scans help diagnose conditions like strokes, hemorrhages, and tumors.

8. *Orthopedic Applications*: Helping orthopedic evaluations, preoperative planning, and postoperative assessments of fractures, joint replacements, and musculoskeletal disorders.

9. *Non-invasive alternative*: Offering non-invasive alternatives to exploratory surgeries, reducing patient risk, discomfort, and recovery time.

10. *Emergency Medicine*: Playing a critical role in emergency departments by quickly providing comprehensive information for timely decision-making in critical cases.

Additional applications include drug R&D, telemedicine, medical education and training. Overall, CT imaging has had a transformative impact on virtually every aspect of medicine and healthcare. Its ability to provide detailed, accurate, and non-invasive information has led to earlier diagnoses, more targeted treatments, and improved patient outcomes.

Finally, A Computational Thinking Perspective

The Computed Tomography's invention, evolution, applications and future improvements present a wonderful story from the viewpoint of *computational thinking*.

CT's invention was by two individuals, Sir Godfrey Hounsfield and Allan M. Cormack, who had backgrounds in engineering and physics, respectively, rather than medical training. Their collaboration and innovative work **broke out of the box** of conventional medical thinking and resulted in a huge breakthrough that is still evolving.

The key ideas leading to the invention were "***reading a closed book from the side, one page at a time***" and "***reconstructing a cross-sectional slice of an inhomogeneous object from X-ray attenuation data at multiple angles***". All these remind us of the computational thinking principle:

> **CT concept–*Think outside of the box***: *Break out of the mold of conventional thinking, challenge old assumptions, create and innovate.*

The solution method of computed tomography first decomposes the problem of anatomical imaging into imaging a number of individual slices which is again decomposed into detecting radiation beam attenuation from multiple angles. The resulting pixel intensities are then combined to form slice images that are then combined into the desired 3D anatomical image. Thus the computational thinking principle:

> **CT concept–*Top-down and bottom-up***: *Keep in mind these powerful problem solving methods.*

The evolution of computed tomography is a typical process of incremental improvement and step-wise refinement, entirely similar to software releases. Thus the computational thinking principle:

> **CT concept–*Make it work then make it better***: *Rome is not built in one day. Make something work first then you have a system to experiment, collect feedback, improve and refine.*

The ever advancing technologies made computers smaller, faster, and more powerful time and again. The accumulation of many such improvements finally made a *quantity to quality change* enabling us to see inside a human body in 3D. How magical! Hence, the computational thinking principle:

> **CT concept–*Incremental improvements can result in something new***: *Enough quantity can turn into a change in quality.*

Applying the concept of **abstraction** from computational thinking we can describe CT scan as: *a technique that detects radiation through the body and then using computers to process the detected measurements to create images of organs or structures within the body.*

Guess what, this definition fits all these medical scan/imaging techniques: CT, MRI, PET, Electron Beam, SPECT (single-photon emission computed tomography), X-ray, ultrasound, mammography.

Furthermore, computational thinkers always want to see how computing can help in any given situation. It is reasonable to think that computer simulation and modeling can play a significant role in advancing the field of CT scanning and medical imaging in general.

This would work by creating a virtual model of a normal anatomical structure, such as a brain, using computational tools. This model would include information about tissue densities, shapes, sizes, and other relevant anatomical features. Then we can simulate the CT imaging process by generating synthetic X-ray projection data based on the known characteristics of the model and the imaging parameters of a CT scanner.

The simulation, once validated, would provide a flexible tool for studying new CT scanner designs, image reconstruction algorithms. Such a simulated CT model would also have applications in training and education. By the way, we have a previous computational thinking blog article dedicated to computer simulation.

Therefore, we have another example of "virtuous feedback cycle" between computer simulation and computed tomography, how perfect!