Gastrointestinal jabberwocky to bioengineering design: using function diagrams to teach physiology

Thad E. Wilson1 and Kim E. Barrett2
1Department of Physiology, University of Kentucky College of Medicine, Lexington, Kentucky and 2Department of Medicine, University of California San Diego, School of Medicine, La Jolla, California

Abstract

Function diagrams put the focus on physiology and physiological concepts rather than the associated anatomy. Function diagrams could potentially serve as an elaboration tool and memory aid (mnemonic) to improve learning and recall. The function diagram prototype of the gastrointestinal system can aid in the instruction of difficult gastrointestinal physiology topics using a sequential focus on fundamental gastrointestinal functions.

INTRODUCTION

“Beware of the Jabberwocky” (see poem), as the nonsensical Lewis Carol (a.k.a., Charles Lutwidge Dodgson) poem begins in Through the Looking-Glass (1). Physiology content is often perceived as nonsensical and difficult to comprehend and recall for undergraduate, graduate, and professional students alike (2, 3). There are many reasons for this student-perceived difficulty, including unfamiliarity due to lack of knowledge transfer or background, too many details, processes that are difficult to follow, and concepts that are difficult to visualize (4). A reductionist viewpoint may compound these difficulties, in that it is often easier to understand an enzymatic reaction, ligand-receptor binding, or signaling cascade, rather than to build a functional biologic unit and then ultimately an entire machine (5, 6). In this Illumination, we will attempt to take the “vorpal blade” of knowledge, “snicker-snack” (see poem), through this Jabberwocky using a bioengineering design approach, by creating function diagrams. The function diagram prototype is of the gastrointestinal system (7), that if viewed through a very distorted lens might just resemble Sir John Tenniel’s famous rendition of the mythical Jabberwocky.

Author T. E. Wilson is repurposing the term function diagrams from what is sometimes used in beginning algebra classes, i.e., a visual plot of the input and output of a mathematical function. The proposed function diagrams also share some resemblance to functional flow block diagrams used in systems engineering and software engineering to describe the interrelationships of a system and the procedural sequence (8). These functional flow block diagrams provide decision points (e.g., go or no go) and are simplified by removing, deemphasizing, or grouping less functional components and showing how the most important components interconnect and interact. The approach sounds well-suited for a biological system, especially in physiology where the operations of cells, tissues, and organ systems form the function of the whole. Simple functional flow block diagrams are currently used to represent various aspects of autonomic reflex arcs, peripheral circulation, or homeostasis in most teaching-oriented medical physiology review textbooks (9–12), but there are also quite complex ones for integrative physiology and modeling (13). However, the sheer number of interconnections and redundancies in a biological system can be difficult to both capture and to visualize. Moreover, classical control systems engineering figures can be off-putting for biomedical and professional students who often approach material without thinking of resistors, parallel circuits, etc., and difficult to recall with their nondescript boxes, lines, and signal indicators.

An anatomy and physiology instructor may rightly criticize diagrams that simplify or remove anatomy, as incorporating the most precise anatomical detail should improve retention of function since these disciplines are inherently coupled. Louis Sullivan’s “Form ever follows function” (14) highlights this notion but is a detailed anatomical approach always helpful to the physiology learner? It is difficult to identify educational based literature to answer this question (Pubmed, ERIC, and Google Scholar using various search parameters in October 2020), although for many years, the curriculum at author K. E. Barrett’s institution relegated anatomy instruction to the second year of the medical school curriculum, reasoning that it would be easier to understand the content with an understanding of physiological processes. It is possible that design not drawn to scale can be a useful method to focus on regulation and function. This may allow for size and proximity to be deemphasized when a particular component’s function is less important to the system, while emphasized
when it is more important or a regulatory or pathological aspect. We believe these creative and emphasizeable freedoms are a significant benefit of this bioengineering approach to construct function diagrams, which put the focus on the function or physiology. Other benefits include the potential for improved learning and recall by incorporating elaboration and mnemonic strategies.

Function diagrams can be used to elaborate key concepts in the learning process, for example, visualizing and adding to various procedural steps and interactions. Elaboration improves mastery of novel material and multiplies the mental cues available for recall and application (15). Physiology and pathophysiology have long histories of using elaboration learning techniques, such as concept mapping (16–19) and clinical decision trees (20). Functional diagrams contain some of the features of concept maps but are also coupled with illustrations that may be able to act as additional mnemonic or memory aid. Linked imagery or memory palace techniques are strongly linked to improvements in recall and are used by most memory competition participants (15).

This specific type of mnemonic makes use of clever locations and images to store information as one visually progresses through a room, picture, or drawing; recently, this technique has been popularized and commercialized for medical students for such topics as microbiology (e.g., SketchyMedical). The clever mechanical analogies for various functions can also improve learning by establishing additional connections for the learner (21, 22). The function diagram approach can be used for any physiological system, for example, the gastrointestinal system. This is where the Jabberwocky (our function diagram prototype) enters the picture: what is more memorable than a mythical beast with prominent gastrointestinal features (Fig. 1) that could eat you (“The jaws that bite, the claws that catch!”; see poem)? Figure 1 is an adapted version of an original diagram that author K. E. Barrett used for more than 25 yr in her introductory lecture to the gastrointestinal physiology segment of a traditional physiology course for first year medical students (and similarly second year pharmacy students). Although popularized by K. E. Barrett’s monograph (7), it was a simplified/streamlined version of one inherited from a valued colleague, Dr. Alan Hofmann. Dr. Hofmann, world-renowned for his detailed exposition of the hepatobiliary system and the mysteries of bile acids, was also a celebrated instructor of physiology and pathophysiology, lauded for his enthusiastic lecturing.

1) Chopper and Grinder: Facial muscles of mastication provide the motive force, upwards of 900 N in some individuals (23), for cutting, chopping, shredding, and grinding oral contents. Incisors, canines, premolars, and molars are all used to reduce particle size to increase surface area and ensure adequate swallowing of ingested food.

2) Hydrolyzer and Lubricator: Oral secretions primarily from the salivary glands (parotid, sublingual, and submandibular) protect and hydrolyze ingested food. The serous secretions also include some enzymes (salivary amylase), protectants (muramidase, lactoferrin, and immunoglobulins), lubricators (mucins), and a buffer (HCO₃⁻). Highlighting the importance of these secretions, conditions that result in xerostomia lead to alterations in taste, an increase in dental caries, and difficulty swallowing.

3) Garage Door and Gear Shifter: The act of swallowing is a bit like an automatic garage door in that it takes thought and effort (pushing the button) to engage the process but the rest is the implementation of a motor pattern and process. This allows nasal and airway passages to be closed, breathing to pause, and the upper esophageal sphincter to open. The initial swallow and subsequent esophageal peristalsis (primary and secondary, if needed) provide the motive force via acetylcholine-mediated contraction behind and vasoactive intestinal peptide/nitric oxide relaxation in front to propel esophageal contents toward and into the stomach. The gear shifter analogy is the important esophageal transition between somatic to autonomic nervous system control and of skeletal to smooth muscle, respectively.

4) Acid Bath, Blender, and Reservoir: The acid bath sterilizer is another strong descriptive analogy as the pH of esophageal contents entering the stomach plummets due to the apical H⁺-K⁺-ATPase of gastric parietal cells. This pH change reduces bacterial flora in dietary and other swallowed secretions (salivary, nasal, and respiratory). Gastric smooth muscle contractions mix, mash, and shift the stomach contents, but like any blender one must put the top on (i.e., contract the lower esophageal sphincter), or there will be a big mess. The reservoir storage function of the stomach allows for more manageable delivery of gastric contents through the pyloric sphincter into the small intestine. It gives special meaning to “rested he by the Tum tum tree” (see poem), interpreted here as waiting in the colloquial “tum-tum” before entering the duodenum.

5) Acid Neutralizer and Enzyme Supplier: HCO₃⁻-rich secretions from the pancreas dilute and buffer H⁺-rich chyme entering the small intestine. This acid reduction allows for digestive enzymes to operate
closer to their pKa. The pancreas supplies the luminal digestive enzymes for chyme-based carbohydrates (pancreatic amylase), proteins (trypsin, chymotrypsin, elastase, and carboxypeptidase A and B), and lipids (pancreatic lipase, cholesterol esterase, and phospholipase A2).

6) **Detergent Supplier and Dispenser**: Hepatocytes are the detergent supplier in the form of bile acids while the gallbladder is the primary detergent dispenser. The gallbladder also concentrates the bile acids, which is analogous to using concentrated rather than regular detergent when washing. The secreted detergent emulsifies fat, which facilitates binding availability for enzymes such as pancreatic lipase. Hepatocytes can also secrete bile acids directly via the bile duct in the form of primary secretions and participate in recycling. Bile acid recycling (returning bile acids to the duodenal lumen following their active reabsorption from the ileum and transfer to the liver) is important for digestion of higher fat meals: who has not needed to add more dish detergent to their wash water when cleaning a late-added pan covered in cooking oil?

7) **Reaction Vessel, Catalytic, and Absorptive Surface**. The small intestine is the location of most of the digestion utilizing luminal enzymes and then its own catalytic apical membrane. Here membrane-bound enzymes (e.g., disaccharidases) complete the digestive process. There is also a pH change near the apical membrane that facilitates lipid release from mixed micelles. Absorption mostly requires a carrier protein for transport across the apical membrane. Examples include the apical transporters sodium/glucose transporter 1 (SGLT1), peptide transporter 1 (PepT1), and fatty acid transport protein (FATP) that transport glucose/galactose, di- and tripeptides, and long chain fatty acids, respectively.

8) **Agitator and Conveyor Belt**. The agitator refers to the mixing movement of the intestines, agitating the chyme to better mix enzymes and facilitate digestion. The conveyor belt refers to the smooth muscle syncytium that participates in peristalsis (see above) and migrating myoelectric complexes and mass movement to facilitate the movement of intestinal contents toward the anus.

9) **Residue Combuster, Dessicator, and Pelleter**: The microbiome is especially active in the large intestine, combusting nonabsorbed nutrients in the chyme. Fermentation reactions form short chain fatty acids for absorption in the large intestine. Water removal (desication) by electrogenic and aldosterone-regulated Na\(^+\) absorption allows for osmotic forces that favor water absorption. The pelleter function refers to the desiccated chyme taking shape in the rectum as water is removed.

10) **Spreader and Emission Control Device**. These final engineering components never fail to bring a smile to the face of the student, even those who are solemn or even “uffish” (see poem). The spreader is an analogy from an agricultural pellet or manure spreader, where composted, granulated, or liquid fertilizer can be deposited in a narrow spread. Flatulence through the emission control device allows the release of some 1,000 ml of intestinal gas produced each day depending on diet, digestive enzymes, and bacterial flora (7). The emissions part is truly climatic, as evidenced from domesticated ungulates’ contribution of methane to global warming (24).

Author T. E. Wilson’s teaching and learning approach incorporated this gastrointestinal system function diagram about 8 yr ago; over the years there have been some minor engineering modifications from the original insightful design (7). He has been teaching medical physiology for 18 years and has been teaching medical students gastrointestinal physiology for ~12 yr. As a topical teaching section, T. E. Wilson found the gastrointestinal system difficult to guide students through, with its high level of epithelial transporter detail, numerous and often redundant control and regulatory factors (e.g., hormones, neurotransmitters, and paracrine

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**Figure 2.** Application of the functional diagram to gastrointestinal motility by focusing on tube transit times and associated sphincters (upper esophageal, lower esophageal, pyloric, ileocecal, internal anal, and external anal sphincters). Figure adapted with permission from McGraw-Hill Education (7).
signaling molecules), separate autonomic nervous system division (i.e., enteric nervous system), and a required oscillatory perspective (jumping between micro- and macrofunctions of the gastrointestinal system). This modified function diagram prototype (see Fig. 1) contained all the essential gastrointestinal functions: secretion, digestion, absorption, host defense, and motility (ingestion, movement, storage, and defecation). Therefore, how does one practically use a function diagram in class and while studying?

Author T. E. Wilson uses function diagrams as the focus of the system introduction with emphasis on essential functions and clinical relevance: this has allowed him to omit initial bullet point lists. Specific areas of the function diagram can then be referred to as coverage progresses to the next gastrointestinal area. Additionally, he uses the function diagram periodically to review previous functional areas, so the student sees where they have been and where they are going. These periodic reviews and bearing checks allow for reflective pauses, often coupled with recall practice, to aid in knowledge retention. T. E. Wilson further modifies (and encourages students to modify) the function diagram to build in customizable gastrointestinal aspects for emphasis or to introduce topics such as motility or pathophysiology (Fig. 2). For example, including transit times and regulated junctions (i.e., sphincters) or binning potential pathologies within a given area/analogy is often helpful. This appears to allow for more connections to take place, whereby the visualization of analogies (e.g., hydrolyzer; enzyme supplier; and catalytic/absorptive surface) can link to the disease processes (e.g., Sjogren syndrome, acute pancreatitis, and lactase deficiency, respectively). Alternately, the analogy can relate to disease-related symptoms. For example, in symptomatic cholelithiasis, gallstones or biliary sludge can cause postprandial right upper quadrant pain, especially after a high-fat meal. Pain can arise with contraction-induced pressure against a temporary stone or sludge occlusion in the gallbladder neck or infundibulum (25). This is analogous to squeezing the detergent dispenser against a closed dispenser outlet. A gallbladder with cholelithiasis can also limit the storage of detergent and if the detergent is not dispensed in adequate amounts into the intestinal lumen, then emulsification is compromised. This renders lipase and colipase less effective, thus affecting fat digestion.

The function diagram prototype of the gastrointestinal system may be able to facilitate the learning of the difficult concepts in gastrointestinal physiology (4), because it visualizes the information in an easy-to-follow manner and contains only the most important functional details. As educators, do we want nonsensical jabberwocky or understanding and long-term recall? The average physiology teacher is a better explainer and conveyor of concepts than Humpy-Dumpty, who was the original poem interpreter (26). This poem is often need help and practice putting the reductionist pieces back together again to remake a fully functional system. The function diagram construction process and its use as a visual memory aid can do this, which may help you hold up a mirror to the nonsensical and slay the Jabberwocky: “Callooh! Callay!”

### Jabberwocky Poem

'Twas brillig, and the slithy toves
Did gyre and gimble in the wabe;
All mimsy were the borogoves,
And the mome raths outgrabe.
Beware the Jabberwock, my son!
The jaws that bite, the claws that catch!
Beware the Jubjub bird, and shun
The frumious Bandersnatch!
He took his vorpal sword in hand:
Long time the manxome foe he sought—
So rested he by the Tumtum tree,
And stood awhile in thought.
And as in utter thought he stood,
The Jabberwock, with eyes of flame,
Came whiffling through the tulgey wood,
And burbled as it came!
One, two! One, two! And through and through
The vorpal blade went snicker-snack!
He left it dead, and with its head
He went galumphing back.
And hast thou slain the Jabberwock?
Come to my arms, my beamish boy!
O frabjous day! Callooh! Callay!
He chortled in his joy.
'Twas brillig, and the slithy toves
Did gyre and gimble in the wabe;
All mimsy were the borogoves,
And the mome raths outgrabe

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### DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

### AUTHOR CONTRIBUTIONS

T.E.W. conceived and designed research; T.E.W. and K.E.B. prepared figures; T.E.W. drafted manuscript; T.E.W. and K.E.B. edited and revised manuscript; T.E.W. and K.E.B. approved final version of manuscript.

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