Hierarchical Knowledge Graphs and their Application

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Abstract: The transformation of the world's knowledge from poorly structured texts, to well-structured knowledge graphs (KG) is a common practice. KGs are well-suited for AI applications, but their human representation can pose challenges for clarity and navigation, especially when dealing with a large number of elements. To address the issue, we propose the introduction of a new type of diagram known as the Hierarchical Knowledge Graph (HKG). Based on the models of cognitive psychology, the HKG has the potential to enhance the use of KGs and ontologies in educational contexts, as it can serve as presentable lecture notes and an alternative to traditional textbooks. This article presents a novel prototype of an application.

Keywords: education; ontology; Knowledge Graph; Hierarchical Knowledge Graph; zoomable book

1. Introduction

The terms *graph*, *knowledge*, and *knowledge graph* are ambiguous. To avoid confusion, we will introduce more precise terminology.

1.1 The Term *Graph*

To understand the ambiguity, let's look at the historical background.

The word *graph* comes from the Greek word *grapho*, which means "*I write*" or "*I draw*".

Figure 1 shows the drawing of Leonard Euler, published in 1741 [4]. This is an illustration of the solution of the *Seven Bridges of Königsberg* problem. This article, by Euler, is considered the foundation of mathematical graph theory [1] [11].

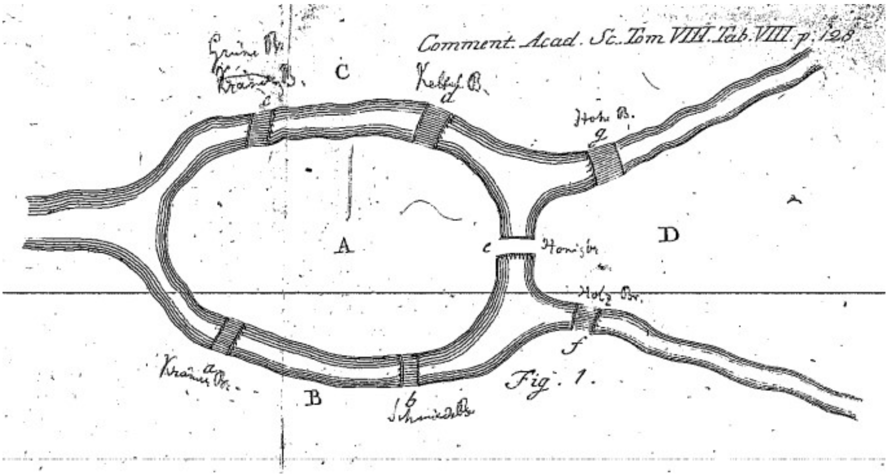

Figure 1

Illustration of Euler for the solution of the *Seven Bridges of Königsberg* problem

Euler's drawing is a geographically incorrect, but topologically correct, simplification of the map of Königsberg. The subject of the problem is the walk between the districts *A, B, C, D* over the bridges *a, b, c, d, e, f, g*. The problem can be studied without the disturbing details of the geographical map. Figure 2 shows a simpler and clearer abstraction of the problem.

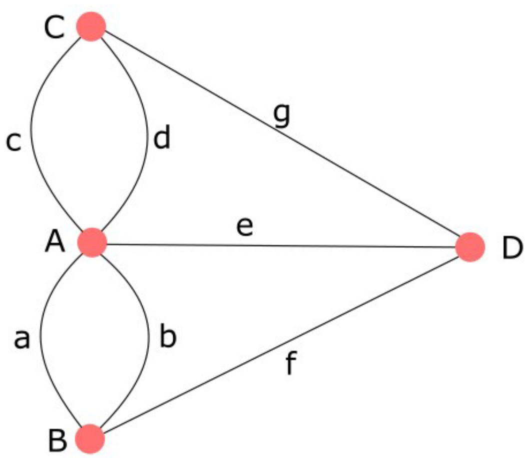

Figure 2

Abstraction of Figure 1

Figure 2 was not drawn by Euler. This type of diagram has only been in use since the second half of the 19th century [6].

In many places, based on this diagram type, the concept of *graph* is defined as:

vertices connected by *edges* (1)

In contrast, graph theory provides a formal definition as follows:

$$G = (V, E) \tag{2}$$

where *G* is a graph, *V* and *E* are sets,

and for *undirected graph:*

$$E \subseteq \{\{x, y\} \mid x, y \in V \text{ and } x \neq y\} \tag{3}$$

for *directed graph:*

$$E \subseteq \left\{(x, y) \mid (x, y) \in V^2 \text{ and } x \neq y\right\} \tag{4}$$

(2) states that the graph *G* is a set, it is the union of the set *V*, and the set *E*.

(3) states that any two different elements in set *V* can be related to each other, and the set of these relations is *E*. The relation between x and y is unordered, i.e., symmetric. (2) and (3) describe the undirected graph. For example, *V* is a set of individuals and *E* is pairs of friends.

(4) says almost the same as (3), but the relationship between *x* and *y* is ordered, i.e., asymmetric. (2) and (4) describe the directed graph. For example, *V* is a set of individuals and *E* is pairs of superiors and subordinates.

The choice of letters *V* and *E* in the (2), (3), (4) definition is not arbitrary; however, they can be substituted with other letters. The mathematical definition describes an abstract structure of entities and relations between them, without reference to the concepts of *vertices* and *edges*.

So, the use of the term *graph* is not clear. Let's introduce the following terminology:

graph diagram: a drawing by definition (1)

graph structure: a structured set by formulae (2), (3), (4)

unordered graph structure: a structured set by formulae (2), (3)

ordered graph structure: a structured set by formulae (2), (4)

A *graph diagram* is a possible but not exclusive way to represent a *graph structure*.

Euler studied a *graph structure* in Figure 1, but he did not use a *graph diagram*.

1.2 The Term *Knowledge*

Knowledge can be categorized into different types, including declarative, procedural, tacit and other forms of knowledge. This text focuses on *declarative knowledge*, which is expressed through declarative sentences about facts. For example:

An aircraft has an airframe and a propulsion system that powers the airframe (5)

Declarative knowledge is also known as theoretical, descriptive, or propositional knowledge.

Cognitive psychology models the structure of human information storage. It defines different kinds of memory. The “semantic memory” stores declarative knowledge. Semantic memory contains concepts of entities, their properties and relationships [14]. The human mind organizes these concepts to enable mental operations such as interpretation, reasoning, decision making, and problem solving. Concepts are organized into the following structures:

- Classification: systematic arrangement of concepts into groups or categories based on their identical properties and attributes.
- Clustering: grouping entities based on similar properties.
- Hierarchization: organizing entities into levels, where except of the highest, each level is subordinate to the one above it. This is typically achieved through hierarchical relationships such as ‘X is part of Y’, ‘set X is subset of set Y’ and ‘class X is subclass of class Y’.
- Linking: connection of entities that are not listed above. Example: A bird lays an egg. The concepts of 'bird' and 'egg' are connected by the predicate 'lays'.

This system can be represented in a *graph structure,* this will become the *Knowledge Graph*.

1.3 The Term *Knowledge Graph* (KG)

The objective of KG is to formalize human declarative knowledge in a way that is suitable for machine processing and simultaneously for human studying. The double requirement claims different representations. Machines are better suited to interpreting data and data structures, while humans are better suited to interpreting visual structures.

Machine Representation of KG

Triple Store

A *triple store* is a set of triples (*X, y, Z*), where *X* and *Y* are related and *y* describes the relationship between them. Triple store is a *graph structure*, it can be undirected or directed depending on the meaning of its elements. This simple structure allows simple storage in a database. (6) shows an example of a *triple store,* which has the equivalent structure as shown in Figure 2.

$$(A, a, B), (A, b, B), (A, c, C), (A, d, C), (A, e, D), (B, f, D), (C, g, D) \quad (6)$$

Resource Description Framework (RDF)

RDF is a standard of the World Wide Web Consortium [15]. It serves as a foundation for machine knowledge representations. The basic RDF model consists of triple statements in the form of (subject, predicate, object), where the predicate describes the relationship between the subject and the object. By reading the three elements of the statement together, a simple sentence is formed, which may not always be grammatically correct, but can be interpreted unambiguously by humans.

RDF triples form a directed graph structure. For example, (7) (8) (9) show the content of sentence (5) in RDF triples.

(aircraft, has, airframe) (7)

(aircraft, has, propulsion system) (8)

(propulsion system, powers, airframe) (9)

In the extended RDF model, attributes can be assigned to each element of the base triples. The machine representation of KG conforms to this framework.

Human Representation of KG

The most obvious visualization of graph structure is the graph diagram. KG management systems, such as WebWOWL, LodView, and Neo4j display KGs in the form of a directed graph diagram.

Figure 3 shows the triples (7), (8), (9) in this format.

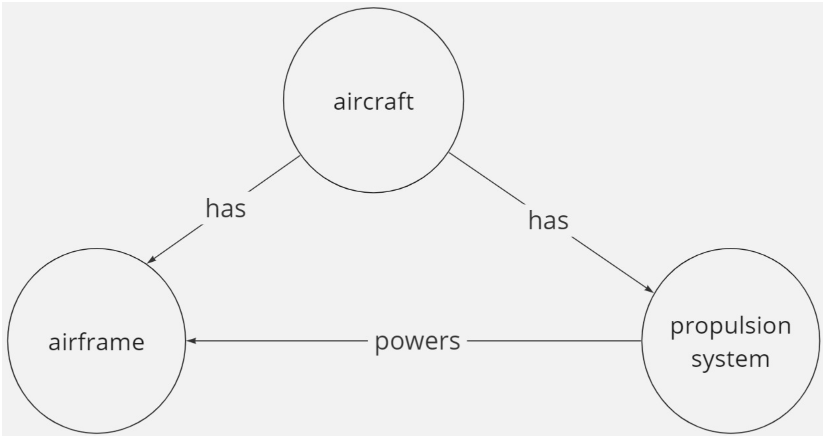

Figure 3
Directed graph diagram

This form may be appropriate for a small number of items, as shown in Figure 4.

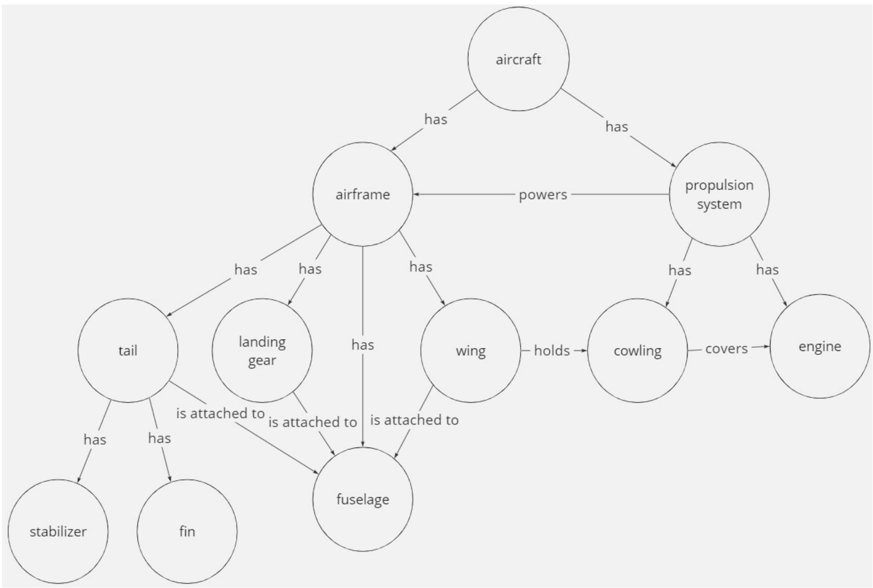

Figure 4
Directed graph diagram with a small number of items

If the number of elements strongly increases, the diagram may become unclear and difficult to navigate. Figure 5 shows two typical displays of KG management tools.

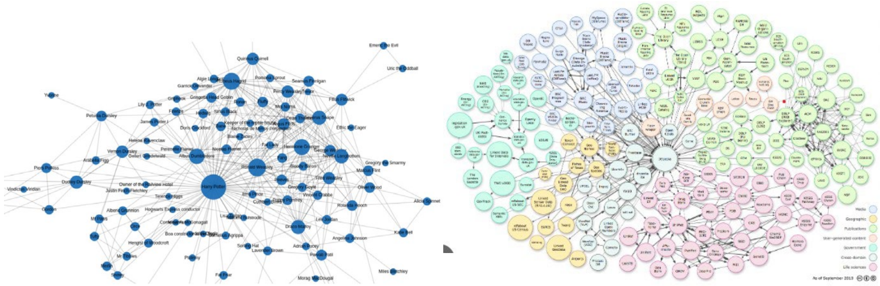

Figure 5
Typical displays of KG management tools

2. Alternative Method

The techniques used will be discussed in the following points.

2.1 Visual Hierarchization – Hierarchical Knowledge Graph

In Knowledge Graphs (KGs), relationships can be categorized as either hierarchical or non-hierarchical. For instance, in Figure 4, the 'has' relation is hierarchical, while the others are non-hierarchical.

Euler was not only concerned with the theory and representation of graphs but also with sets. The following Euler diagram represents sets and their subsets with nested shapes. For example, in Figure 6, set *Y* is a subset of set *X*.

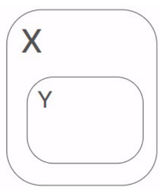

Figure 6
Euler diagram for set and subset

We propose to combine the KG diagram with the Euler diagram so, that hierarchical relations are represented by nested shapes and only non-hierarchical relations are represented by edges. This new diagram type is called Hierarchical Knowledge Graph (HKG).

Figure 7 shows an HKG, as a transformation of the KG in Figure 4.

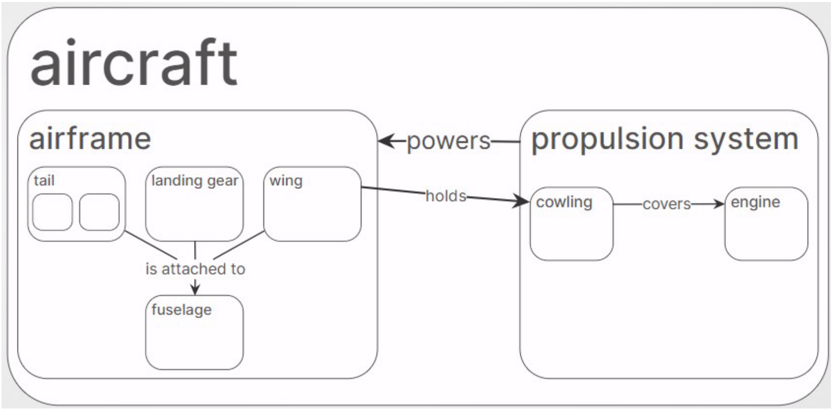

Figure 7
Hierarchical Knowledge Graph – isomorphic to KG in Figure 4

In the example above, there are three levels of hierarchy presented clearly. However, the shapes of the fourth level are too small, making their content unreadable. The use of the Zooming User Interface (ZUI) can assist coping with this.

2.2 Zooming

Zooming enables synchronized mental and visual focus on a specific part of a complex object. For instance, if someone wants to study the details of the *airframe* in Figure 7, they can zoom into the corresponding box. Figure 8 demonstrates that the elements of the fourth hierarchy level also appear by this operation.

ZUI allows for the management of any number of hierarchy levels, in a fractal manner. This means that the same structural and visual concept applies to each level.

Advantages of HKG over KG include:

- The ability to represent an unlimited number of entities in a limited area
- Presenting a manageable number of entities at each level improves comprehensibility and avoids cognitive overload
- Easy navigation in the hierarchical tree structure
- Maintaining context while studying details

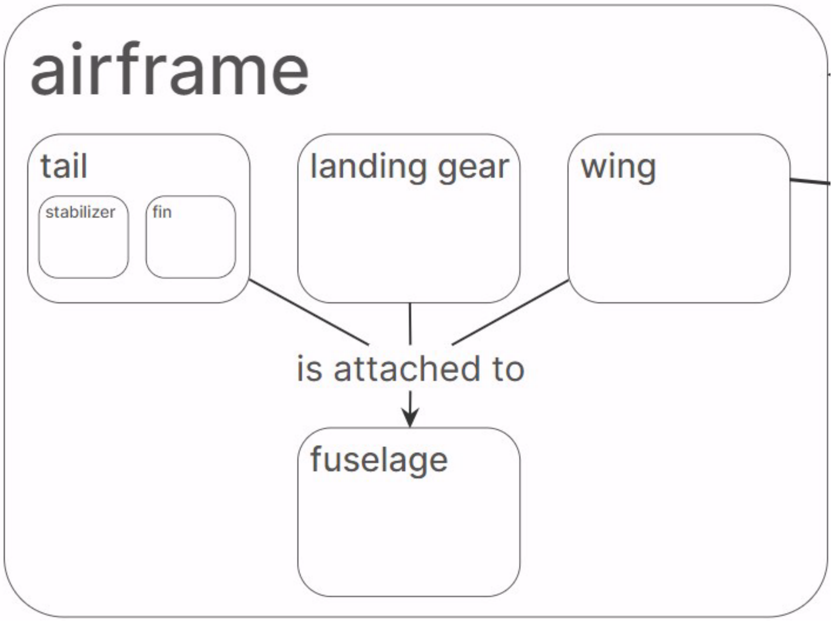

Figure 8
Enlargement of the airframe box in Figure 7 by zooming in

Analogies to the Zoomable Geographical Map

A map's objects form a hierarchy, with continents containing countries, which in turn contain cities, and so on. The subordinate object's image is nested within its superordinate item's image. The placement of the objects on the map depicts their relations. Therefore, the objects on a geographical map form a HKG structure, with a unique representation. Google Maps demonstrates the ease of visually navigating among millions of entities using ZUI for this structure. To present the HKG, it is advisable to utilize the following methods.

Semantic Zooming

Semantic zooming refers to the phenomenon where, at a certain zoom level, an object's figure is replaced by a more detailed representation of the object, rather than simply being enlarged. For instance, a circle on a map denotes a location, and zooming in reveals a more detailed road network of the same area.

Parallax Zooming

Parallax zooming refers to the phenomenon where the change in scale size and/or position of an object differs from the change in other objects during zooming. For instance, the font size of a tag does not increase proportionally to zooming, but rather increases to a lesser extent or remains constant. See labels on a zoomable geographic map.

Using of Overlays

Overlays are the layers of information that appear above the zoomable canvas and move with it during zooming. Users can turn the appearance of overlays on and off. Examples of overlays on the geographic map include traffic information, hotels and shops.

In HKG, entities belonging to the same class should be organized in the same overlay. For example, in an anatomy ontology, the main display can present the hierarchical system of body parts, while additional overlays can show the organs, bones, arteries, and other components.

3. Potential Applications

3.1 Display of Ontologies

In information science, an ontology is a machine-readable knowledge base that describes the concepts, properties, and relationships of a domain. Its structure corresponds to a graph structure. However, ontology management tools, such as Protégé, display the content in hierarchical format for human use instead of a graph diagram. The issues with the graph diagram discussed in Section 1.3 are the likely reason for this.

Figure 9 shows a scene from the disease ontology of the University of Maryland School of Medicine [12]. The left bar allows for expandable-collapsible hierarchical navigation. Selecting an entity displays its corresponding data sheet on the right. However, relationships between entities can only be accessed through links on the data sheets, making them less easily overviewed than in a KG.

HKG is recommended for displaying ontologies because it combines the advantages of graph diagrams and hierarchical displays while eliminating their disadvantages.

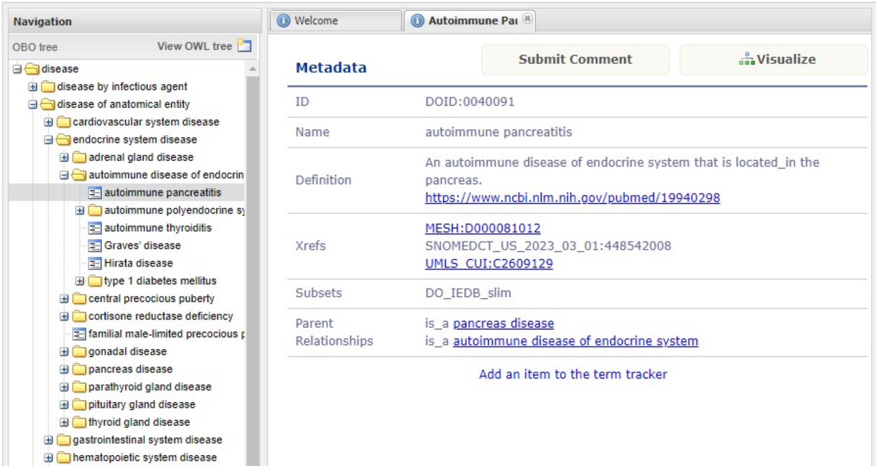

Figure 9
Hierarchical display of the disease ontology

3.2 Note-taking

Note-taking works as a second brain. It improves learning and memory, supports mental processes such as thinking, decision making, problem solving. Cognitive psychology considers the structure of information important in these processes. It is much easier to represent structure visually than textually [2], so the evolution of note-taking is moving toward visuality. The Mind Map, Concept Map, Knowledge Graph series with a graph structure are getting closer to the semantic memory models established by cognitive psychology.

The methodology of using the Personal Knowledge Graph (PKG) can be considered as developed by [10] [13]. Research proves its importance in the learning process [3]. As a state-of-the-art note-taking tool, Obsidian introduced the possibility of using PKG [7].

Hierarchy is one of the most important structures in human thinking, so it is recommended to include HKG respectively the corresponding hierarchical PKG in the set of note-taking tools.

3.3 Lecture Notes as Presentation and Learning Tool

The instructor's task is to select a subset of knowledge and determine how to convey it to students based on didactic aspects. It is recommended to prepare a visual presentation to support the oral presentation and provide written notes for individual learning.

If the concept system to be taught already exists in an ontology, the appropriate subset can be selected and displayed in a HKG. The advantage of zooming is that there is ample space for placing images and additional textual information next to each concept. The HKG expanded in this way is called a *z-book* (zoomable e-book). The instructor can utilize the upper levels of the z-book as a presentation tool to demonstrate the concepts of the subject area and their connections, while the lower levels provide detailed knowledge and explanations for individual student learning.

A Prototype of z-book

In the EUROSTARS-2 call for proposals, we implemented a project called "z-book" in a consortium with the Universitäts Klinikum Heidelberg (hereafter referred to as UKHD). The project involved creating a German-language prototype on the topic of anatomy titled 'Pankreas im Fokus'. The prototype is accessible upon completing the registration process [9].

Figures 10-14 show some characteristic details of the prototype.

Figure 10
Major topics at the top level of the hierarchy

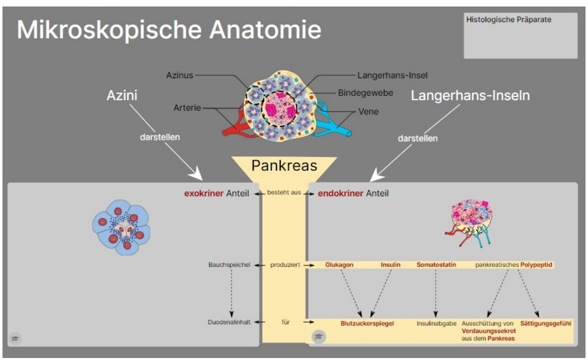

Figure 11
Zooming in to the next level - concepts linked to pictures, connections between concepts

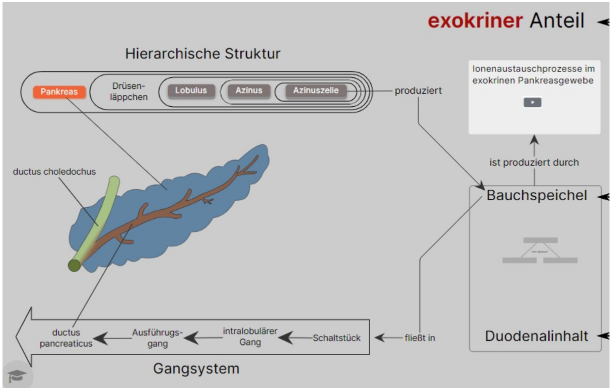

Figure 12

Zooming in to the next level – refined structure of concepts

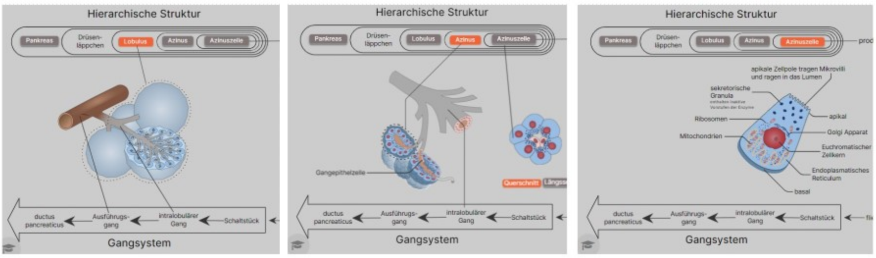

Figure 13

Use of overlays with pushbuttons

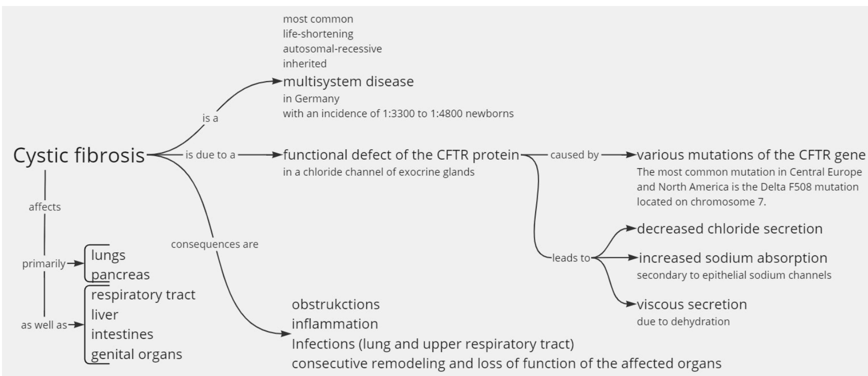

Figure 14

Structured description of a clinical case (translated from the German z-book into English)

Advantages of Lecture Notes in z-book Format

- It can be semi-automatically generated from an ontology
- The layout is adapted to the process suggested by the learning and reading strategies. An often-quoted summary of this is provided by Ben Shneiderman [8]:

Overview:	Gain an overview of the entire collection
Zoom:	Zoom in on items of interest
Filter:	Filter out uninteresting items
Details on-demand:	Select an item or group and get details when needed

- Students can study the details in the visual structure learned during the lecture. This can speed up the learning process

Experiences of Use

UKHD benchmarked the z-book by using multiple-choice exam questions. The experiment involved 16 z-book users and 38 non-z-book users. The exam results indicated no significant difference between the two groups. The 16 z-book users spent an average of 72 minutes studying the material to prepare for the exam, indicating effective learning. The z-book users spoke positively about the learning experience, citing the clarity, interpretability, and navigability of the material as advantageous. Additionally, they expressed interest in using similar media in the future and recommending it to others.

Unfortunately, this study does not scientifically prove that the use of the z-book is more effective than the use of a conventional textbook. Further experiments are needed to validate our hypothesis.

Conclusions

The use of KGs is expanding rapidly due to their interpretability by both humans and machines. To enhance human understanding, hierarchical visualization can improve clarity and navigability. Although the initial experiment with HKG yielded promising results, further testing is necessary to validate our hypotheses.

In future experiments, it is recommended to use problem-solving questions. This is because meaningful learners have an advantage over rote learners in this type of question. Gonzales et al. conducted a study and found no significant difference between the two groups in multiple-choice exams [5].

Acknowledgement

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