



The Graphic Novel: A Promising Medium for Learning Research

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All education requires a medium for facilitating learning. Oral education gave way to books, which have remained an educational staple until the present day. Thanks to the Internet and more recently massively open online courses (MOOCs), learning through video has become more widespread than before (see [1], [2] for review). As we become more familiar and proficient with creating these multimedia artifacts, we can better understand their limitations and possibilities. Videos can offer an audiovisual experience that evolves in a linear manner. Books can offer a multimedia experience (mainly a verbal-visual one) that readers can determine the rhythm of by controlling their reading speed and selection. A medium exists that lives somewhere between books and videos: graphic novels.

While graphic novels are firmly established in the global and especially American cultural landscape, they are severely under-utilized in the facilitation and research of learning. This paper explores, first, what a graphic novel is, second, how they are and can be used for education and learning research, and, third, possible concrete steps to fully realize the medium's instructional and research potential. The ultimate purpose of this paper is to raise awareness about graphic novels and point out barriers and ways to overcome barriers that the general learning research community and the specific STEM learning research community can rally around.

What is a graphic novel?

While the graphic novel shares features of a textbook and of a video, it also brings something distinctly unique to the wider media landscape. At core, a graphic novel is composed of pages that contain other elements. The fundamental elements include panels (outlined visual containers), speech containers, visuals, and text [3], [4]. The spatial organization of these elements and stylistic rendering provide the basis for a distinct visual identity of any given graphic novel [5], [6]. For example, every page in *Watchmen* [7] has an arrangement of nine panels and *Jimmy Corrigan: The Smartest Kid on Earth* [8] has block arrangements of all panels, while *Maus* [9] has no specific spatial organization (see **Figure 1** for two example pages).¹ Furthermore, each graphic novel follows a narrative. The plot, characters, setting, and themes provide the basis for a graphic novel's distinct narrative identity. Some graphic novels follow a particular character (e.g., *Iron Man*²) or the effects of one event on an ensemble of characters (e.g., the *Civil War* storyline [10]), while others still follow a particular abstract exploration (e.g., *Unflattening* [11]). The intertwining of these two identities is of paramount importance because a graphic novel is not equivalent to a sequence of textbook illustrations – a graphic novel is a storytelling medium. In fact, a graphic novel can have another comics embedded inside it (as in *Watchmen* [7]) or a transcript of a conversation rather than the showing of it (as in *Pax Romana* [12]). It is a versatile medium both in form and function.

¹ Because this paper acts as an introduction for many readers into the world of graphic novels, the paper includes the titles of many comic books and graphic novels, so that readers can choose to pursue any one based on interest or intuition. All of the works are either fully cited at the end of the paper or linked to in footnotes. Where appropriate, the paper also provides short descriptions of the plots and themes of specific works.

² You can find out more on the following website: http://marvel.com/characters/29/iron_man.

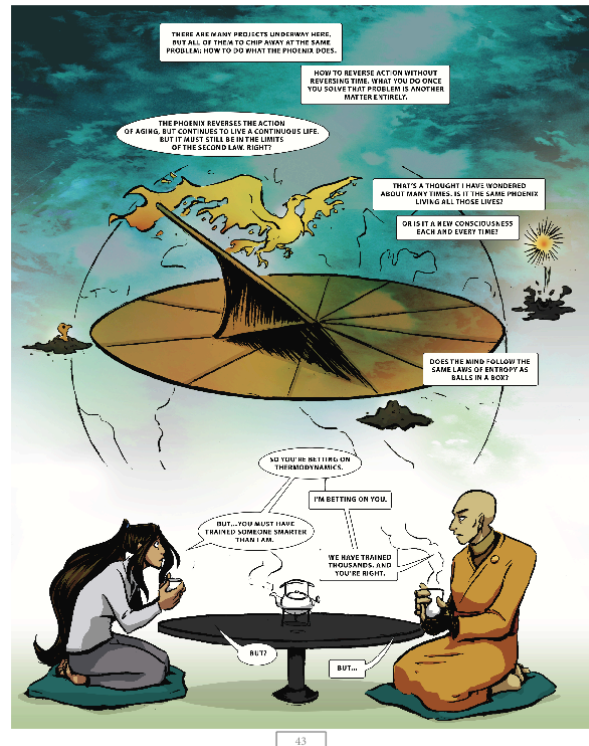
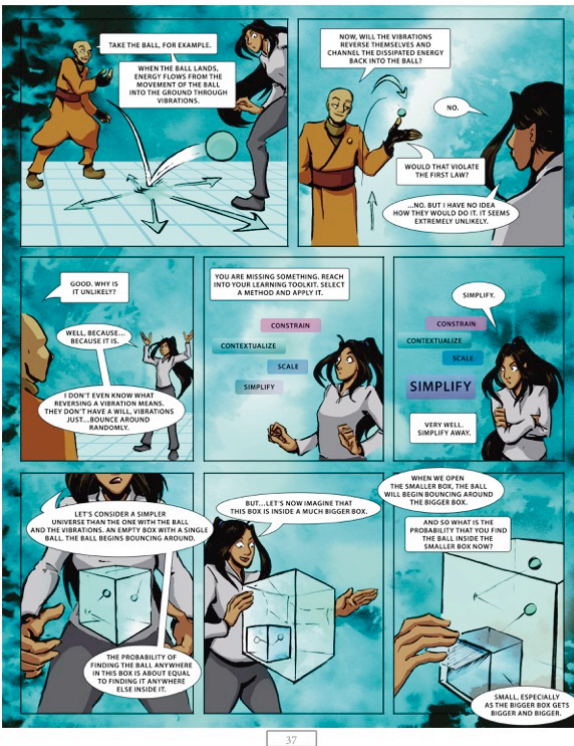


Figure 1. Shows two pages from *The Phoenix Corps* (<https://www.thephoenixcorps.com>), a graphic novel whose creative team includes the author. The left page shows grid-based panel organization as well as combining learning about thermodynamics, learning about how to learn, and learning through analogy/metaphor on a single page. The right page shows a non-grid-based visual style centered on metaphysical questions.

Graphic novels are not alone in using the aforementioned elements, though. Comic strips (such as *Dilbert*, *Long Story Short*, or *Wizard of Id* that one can find in a newspaper³), comic books (such as issues of *Batman*⁴, *Iron Man*⁵, *American Gods* [13]), and web comics (such as ⁶ *xkcd*, *PhD*, *Newton and Copernicus*) all use the same elements [4]. The scale of what they can sustain, however, differs. Comic strips sustain a narrative that pays off within several panels and does not need much more space beyond that. Comic books generally sustain a narrative for a couple of dozen pages that can at once act as a standalone plot and as part of a more expansive tale. A graphic novel can sustain a narrative that spans dozens or hundreds of pages, as is the case with the *Civil War* [10] and *Infinity* [14] compilations. To specify the distinction between a comic book and a graphic novel, Baetens and Frey [4] suggest looking at four features: form; content; publication format; production and distribution. In terms of form, comic books generally follow more established guidelines in terms of layout and composition, whereas graphic novels can generally

³ You can also find these on the following websites, respectively: <http://dilbert.com> and <https://www.arcamax.com/thefunnies/longstoryshort/> and <http://www.gocomics.com/wizardofid>.

⁴ You can find out more on the following website: <http://www.dccomics.com/characters/batman>.

⁵ You can find out more on the following website: http://marvel.com/characters/29/iron_man.

⁶ You can find out more on the following websites, respectively: <https://xkcd.com> and <http://phdcomics.com> and <http://www.newtonandcopernicus.com>.

explore visual treatments and composition styles with greater freedom. In terms of content, graphic novels tend to take on more serious and sophisticated themes as well as to be grounded in realism (not in opposition to science fiction, but in pursuit of autobiography or history). In terms of publication format, comic books tend to favor short-format prints that lend themselves toward serialization, whereas graphic novels tend to adopt more of a traditional book format that presents more of a complete, singular work. In terms of production and distribution, comic books tend to be published and distributed to the mass market by established powerhouses, whereas graphic novels have historically had an independent publisher streak and to this day offer much more flexibility in how to be introduced to the market. As one can see from this list, distinguishing formally and unequivocally between the comic book and the graphic novel is not a straightforward endeavor! To summarize, in comparison to comic books, graphic novels can: display greater flexibility in their visual style, handle more sophisticated and grounded narratives, take on a book format as a singular rather than serialized work, and make its way into the hands of readers through independent efforts or publishing arms separate from large comic book companies.

Graphic novels as educational medium

Understanding the content that graphic novels choose to tackle is critical from a learning perspective. The themes do tend to be more adult⁷ and the stories tend to be thematically complex. Some stories focus on re-telling historical and/or biographical plotlines such as the Holocaust through *Maus* [9], life in revolutionary Iran through *Persepolis* [15], or Bertrand Russell's personal struggles to invent a branch of modern mathematics through *Logicomix* [16]. With the last example, readers can be learning as much about Bertrand Russell's life in the Europe of his time (history) as they are about set theory (mathematics) and questioning the motivations and consequences of one's knowledge contributions (philosophy). Other stories focus on fantasy worlds or science-fiction scenarios such as a superhero-based alternative timeline of Victorian England (*Marvel 1602* [17]) or a time-traveling detective/archaeologist squad (*Planetary* [18]). Within the superhero genre, storylines routinely tackle emotionally complex and socially relevant themes. *Civil War* [10] takes on issues of discrimination and government oversight of legally unaccountable superheroes (thanks to which readers can learn about social justice and philosophical issues). *Planet Hulk* [19] explores how to find a sense of peace and stability when one can neither die, nor be trusted enough by those around him to exist in a safe society (thanks to which readers can learn about ethics). *Secret Wars* [20] explicitly asks the question: if you could re-make a multi-verse, who would you entrust the task to...and what kind of a world would we end up with (thanks to which readers can learn about physics, philosophy, and psychology)? Many examples of graphic novels with these and other themes exist. Too many to name. The overall point is that graphic novels generally explore multiple strands of material within a single story and show the potential for readers to learn from them.

In this vein, graphic novels have already found a place in the classroom. *Maus* (an autobiographical and biographical work about the Holocaust) [9], *Trinity: A Graphic History of the First Atomic Bomb* (a historical and scientific explanation of inventing the atomic bomb) [21], and *Persepolis* (an autobiographical work of a woman's life in post-revolutionary Iran) [15] are all examples of graphic novels that could be and/or are being used in history classrooms, for instance. In science,

⁷ This paper focuses on graphic novels for a high school, college, and adult audience. While some parallels between children's learning and graphic novel learning can offer valuable insights, that investigation is outside of the scope of this paper.

technology, engineering, and mathematics (STEM), *Neurocomic* (a romantic story about neuroscience and biology) [22], *Logicomix: The Epic Search for Truth* (a biographical work about the advancement of set theory) [16], and *Strange Attractors* (a mystery thriller about dynamic systems theory) [23] can be used for instructional purposes. STEM topics have already received a graphical/visual treatment in various instances (see **Table 1**). This most likely arises from a combination of many STEM topics being amenable to visual explanation and of learning STEM topics being in high demand.

Title	Type	STEM Topic	Audience
Science Stories: Amazing Tales from Rothamsted Research Lab	Online Comic	Biology (Insect Research)	12-18
Beatrice the Biologist	Short Comics	Biology (Natural World)	K-12
Neurocomic	Graphic Novel	Biology (Brain and Neuroscience)	K-12
PhD	Web Comic	Science Process (Graduate Research)	16+
Saturday Morning Breakfast Cereal	Web Comic	General Science	16+
xkcd	Web Comic	General Science	16+
Max Axiom	Comic Books	General Science	12-18
Science: A Discovery in Comics	Graphic Novel	General Science	12-18
Boxplot	Short Comics	Physics (Astrophysics)	16+
Trinity: A Graphic History of the First Atomic Bomb	Graphic Novel	Physics (Nuclear Physics)	12-18
Secret Coders: Paths & Portals	Graphic Novel	Computer Science (Logic and Programming)	8-12
Logicomix: The Epic Search for Truth	Graphic Novel	Mathematics (Logic and Set Theory)	16+
Strange Attractors	Graphic Novel	Mathematics (Dynamical Systems)	16+

Table 1. Presents a sample list of various visually-based narrative media organized by their publication type, STEM topic, and age of audience. The sample in this table showcases media primarily in the young adult and above age range (considered here to be 16 years or older).

Because of the use of graphic novels in the classroom, some academic literature now exists on the graphic novel as a literary medium (*Graphic Novel: An Introduction* [4]) and on the graphic novel as a teaching medium (*Teaching the Graphic Novel* [24]). Especially from the latter, a collection of essays by teachers who used graphic novels in their classrooms, we can glean insights about the learning-facilitation capacities of this medium. One capacity is to use narrative as motivational momentum to carry readers through unpleasant and/or uncomfortable visual experiences. This matters because “stunning visuals might repulse readers before they have had the opportunity to become engrossed in the story... simply catapulting unprepared readers into the heart of Auschwitz

might lead them to exit just as quickly” [25, p. 242]. Using medium-specific elements (in this case, investment in story) as a vehicle for learning has clear parallels to the use of gameplay and interaction in game-based learning [26]. Another capacity is to use the protagonist’s experience as a proxy for the reader’s experience. Especially if the creator and/or instructor knows what prior knowledge or what questions the reader might have, the graphic novel can use the protagonist to address them specifically. *Uncle Sam*, a graphic novel about some of the most important and uncomfortable events in the history of the United States, follows Sam, the protagonist on his journey through these events. As Nichols explains, the “historical episodes to which Sam (and, by proxy, the reader) is made privy provide a sure antidote to any jingoism that traditional accounts might engender” [25, p. 240]. This moment kind of learning is possible only when a learning designer knows enough with enough precision the knowledge state of the intended learners as in other fields of learning research such as knowledge modeling [27] and misconception research [28], [29].

Graphic novels as a research medium

As the previous section illustrates, graphic novels already exist to facilitate learning, but research into learning – rather than teaching – with graphic novels has not developed robustly. There are possibly at least three reasons for this. The first reason is a prevailing bias of graphic novels and comic books as childish or simply not a mature medium to use in instruction [4], [30], [31]. This is perfectly understandable. If one interacts with this medium only (1) during childhood, (2) when reading a funny section of a newspaper, and/or (3) as something to intellectually avoid from the opinions of teachers and others, then such a negative perception can develop. An apt analogy would be as if someone stopped watching animated films because one’s main association with the medium is Saturday morning cartoons. One would miss out on complex and impactful stories such as *Ghost in the Shell* (a science fiction narrative about biological as well as social identity in hyper-connected world rife with artificial intelligence) [32], *Spirited Away* (a young girl’s struggle with identity told through her liminal journey in a magical world) [33], or *Grave of the Fireflies* (story of two siblings in World War II Japan after the firebombing of Tokyo) [34].

The second reason is that graphic novels require a specific skill set and usually a team of people to make. Making a graphic novel is not the same as writing a course reader or an essay. More importantly, we do not receive as much exposure to or training in making graphic novels as we do in writing essays or course readers in current formal education [30]. If an instructor needs to, he/she can write a textbook alone and with very few special resources. Making a graphic novel is more involved, although one could probably put together low-fidelity drafts of certain pages, mimicking a Microsoft Word version of an eventually professionally typeset manuscript. Nonetheless, graphic novels generally require more advance planning and a team.

The third reason is that graphic novels are traditionally impossible to edit. The traditional way of making graphic novels involves writing a script, creating page layouts, penciling, inking, coloring, and lettering. All of this is done physically on paper and then scanned into digital form. This means that creating alternative versions of a page is not as simple as editing a Microsoft Word document. Creating alternative versions involves either making completely new versions of the same page or engaging in creative digital splicing of separate scans [3]. In other words, traditionally-made graphic novels are not an easily editable medium, which is a requirement for facilitating as well as researching learning.

Despite these major (and other associated) reasons for not conducting learning research with graphic novels directly, learning researchers have been interested in the individual elements that comprise a graphic novel. For instance, substantial research has investigated the interplay between the spatial positioning of images and text for learning [35], [36], the role of discourse in learning and teaching [37], [38], and the methods of argumentative reasoning [38], [39]. For graphic novels with educational goals, educators and researchers can also look to research into worked examples [40], the epistemological standards of various forms of explanation [41], and the nature and effects of digital simulation [42]. Graphic novels could serve as a focal point for these disparate literatures thanks to its visual and dialogic nature. At the same time, because graphic novels blend all of these possible learning mechanisms in such complex ways, new research methods might need to emerge to fully capture the complexity.

Beyond becoming a medium for investigating the combined effects of these learning mechanisms, graphic novels could provide a powerful medium for several aspects of STEM-relevant learning specifically:

- **Modeling problem-solving behavior and norms.** Graphic novels can show the internal/cognitive around the steps of how to solve a problem rather than just the steps or just the reasoning separately. Especially when showing a scene with multiple learners engaging in a problem-solving process, graphic novels can model specific behaviors and norms, such as socio-mathematical norms [43], [44]. One powerful instance of this would be showing how learners negotiate the content as well as epistemological implications of different problem-solving approaches (called epistemic games) [41], [45]. A graphic novel could show fictional learners deciding between two competing solutions in a socially respectful, epistemologically responsible, and scientifically productive manner so that real-world learners can model those behaviors through their own experiences.
- **Conceptual change.** The mechanisms for conceptual change remain complex creatures [28], [29]. What graphic novels could bring to conceptual change research is facilitating the process in this unique blend of visuals and dialogue and also showing a character undergoing the process of conceptual change itself. Here, we can even imagine showing a character's knowledge structure change following a critical epiphany. One particular subset of conceptual change literature that could benefit from using the graphic novel medium is research into conceptual change metaphors. These are metaphors that facilitate conceptual change, and they tend to be visual in nature, such as angry bees as ways to show atomic behavior related to entropy [46], [47]. Showing these metaphors in a graphic novel while a character is simultaneously explaining them might make for a more powerful and clearer learning effect than only reading about them.
- **Dialogic/Discourse assessment.** Since graphic novels rely so heavily on conversation (internal or external), they can inspire assessments around explanation, argumentation, and other forms of discourse [37], [38]. What does it mean to speak like a scientist? [48] What analogies would one use to explain a particular concept to a fictional colleague? [49] In the format of graphic novels, we can gauge how learners command knowledge in conversation rather than in paragraph-based written prose or calculation. This could be particularly useful for surfacing misconceptions that might be difficult to reveal with multiple choice questions or calculation, such as misconceptions around entropy and the Second Law of Thermodynamics [50].

Other fruitful areas for research exist – the areas above are illustrative, not exhaustive.

The point is not only that graphic novels can enable the learning research above, but primarily that graphic novels can enable the learning research above in a different way than more traditional learning research media can. For instance, enabling dialogic/discourse assessment can be expensive, requiring either in-person interviews with students [51] or group-based tasks that have discourse steps but the ultimate deliverable is not discourse (e.g., but a written essay [52]). Graphic novels can create a more natural dialogic environment (i.e., the speech between characters) in which to learn and in which to assess, thereby reducing the cost and complexity of this kind of learning research. Furthermore, bringing in the two learning-facilitation capacities from an earlier section, learning researchers can use the narrative to establish a motivation for students to persist in the learning assessments and the characters as proxies for students' experiences. Characters can make the reasoning moves that the students are prone to making and ask the questions that the students are prone to asking at that stage in their learning journey. Again, however, since a robust literature on graphic novel learning does not currently exist, understanding the unique learning processes that graphic novels can facilitate needs to be part of the wider research agenda.

What is the best path forward?

The question, then, is not *if* graphic novel can play a role in facilitating and researching learning, but *what* role graphic novels can most reliably play. And how we need to evolve the medium to allow it to fulfill its research potential.

The role of graphic novels is not necessarily to replace textbooks in full as the main method of delivering instructional content. Textbooks tend to be well-suited for presenting information in a highly organized and logical manner. And with significant mathematical (or other discipline-specific) notation to go along with it. They might even show worked examples and include short historical references. Graphic novels could supplement formal modes of instruction by (1) modeling learning behaviors and norms, (2) lending a historical context to a subject, (3) engaging learners with a story that immerses them in the subject, and (4) possibly eases specific social or academic anxieties about learning. To explain the last point, imagine that a graphic novel shows a learner acknowledging (internally or externally) anxieties about racial stereotypes or the difficulty of the material or even one's worth or ability to learn related to all the other learners. If authentically-crafted and well-presented, experiencing such a scene might normalize those anxieties and let real-world learners know that they are not alone with those feelings and anxieties. On an instructional level, a graphic novel could show characters navigating their way to a clear understanding (through dead ends, what ifs, and misconceptions), whereas textbooks could present the necessary formalism and examples to create a robust knowledge structure. In this way, we could begin to distribute learning facilitation functions across media rather than compressing all of those functions into a single medium (see **Figure 2**). There is no one medium to rule all learning.

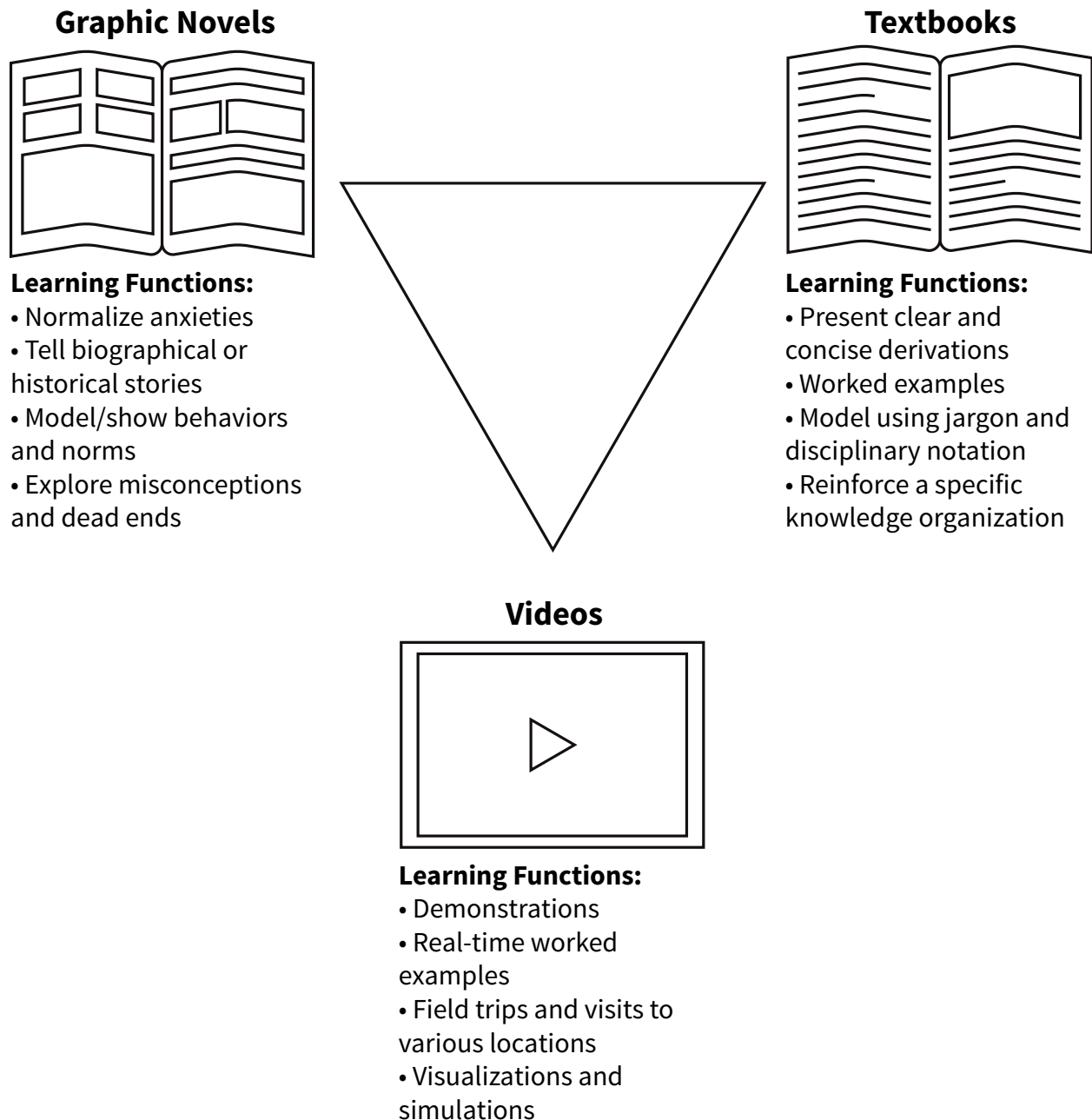


Figure 2. Shows the distribution of various learning functions across at least three media: graphic novels; textbooks; and videos.

The difficulties with using the medium for research mentioned earlier remain, however, and to realize graphic novels' potential for research, we need to find ways to overcome them. The first step in this direction is to find a way with digital technology to render graphic novels editable [3]. On one hand, being able to edit text would be a realistic next step. On the other hand, being able to swap out some of the instruction-relevant images would be ideal. With these editing capabilities, graphic novels become amenable to iteration and production of alternative versions, a key feature of a learning research medium. Another step is in finding ways to embed assessment directly into the graphic novel medium. Imagine being able to write in a response to a conversation, select which

character to talk to, or adjust a visual on behalf of a character. With these interactive capabilities, the medium becomes a platform for assessment that are visually and story-wise consistent with the rest of one's experience. In other words, if well-executed, the assessments do not need to take one out of the wider experience.

These interaction, assessment, and editing capabilities also open the door to making one's graphic novel both personal as well as personalized. Personalized in the sense that the content could adapt based on one's interactions [53], [54]. Personal in the sense that, by the end, the resulting graphic novel would contain a record of one's own unique interactions. This is a particularly exciting future to pursue because each learner exits the experience with his/her own story. The graphic novel represents one's own choices and responses and solutions to the situations presented by the graphic novel. While it might not make a lot of sense to read through someone else's marked-up textbook, it would make sense to read through someone else's unique graphic novel.

Finally, we need to find ways to reduce the cost and complexity of making graphic novels. Put more precisely, we need to find ways to reduce the cost and complexity of creating the *precursor materials* for making a graphic novel. Making a graphic novel will most likely remain a team experience. Re-inventing that process might be too difficult at this point in time. Lowering the barrier to creating precursor materials to make the team enterprise clearer and easier seems a more feasible problem to tackle. Here, we can imagine creating templates for certain pages that allow instructors to draft conversations and visuals or creating a world/setting within which multiple stories can be told might be productive next steps. The latter possibility would allow for teams to easily share resources, so that not every graphic novel needs to invent a new wheel, so to speak. Effectively, the goal would be to create a shared universe that multiple subjects and storylines can occupy. Therefore, the main challenges to making graphic novels a researchable medium reside in how to (1) lower the cost and complexity to make them (which could include sharing resources across projects), (2) improve the capability to edit them, and (3) increase our capacity to embed interactions and assessments into them. As a final note, researching teams that are working on a graphic novel might be an important contribution to understanding how to better facilitate the process.

Conclusion

Graphic novels are already – albeit infrequently and unsystematically – used to facilitate learning, but not at all to research learning. This trend is understandable due to prevailing perceptions of graphic novels as a medium for primarily childhood entertainment and also due to the cost and complexity associated with making, editing, and assessing them. This is a pity because graphic novels present a powerful medium that can supplement other media, especially textbooks in facilitating learning. Finding ways to overcome the current challenges with the medium to make it amenable for use in instruction and learning research can only benefit the learning research community.

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References

- [1] D. L. Schwartz and K. Hartman, "It is not television anymore: Designing digital video for learning and assessment," *Video Res. Learn. Sci.*, pp. 335–348, 2007.
- [2] L. R. Lagerstrom and P. Johanes, "Online Videos: What Every Instructor Should Know," *Comput. Educ. J.*, vol. 8, no. 1, pp. 67–79, 2017.
- [3] S. McCloud, *Reinventing Comics: How Imagination and Technology Are Revolutionizing an Art Form*. HarperCollins, 2000.
- [4] J. Baetens and H. Frey, *The Graphic Novel: An Introduction*. Cambridge University Press, 2015.
- [5] M. Madden, *99 Ways to Tell a Story: Exercises in Style*. Penguin Group, 2005.
- [6] N. Cohn, *The Visual Language of Comics: Introduction to the Structure and Cognition of Sequential Images*. Bloomsbury Academic, 2013.
- [7] A. Moore, *Watchmen*. DC Comics, 1986.
- [8] C. Ware, *Jimmy Corrigan: The Smartest Kid on Earth*. Pantheon, 2003.
- [9] A. Spiegelman, *Maus*. Pantheon, 1996.
- [10] M. Millar, *Civil War*. Marvel Characters, Inc., 2011.
- [11] N. Sousanis, *Unflattening*. Harvard University Press, 2015.
- [12] J. Hickman, *Pax Romana*. Image Comics, 2008.
- [13] N. Gaiman, *American Gods Volume 1: Shadows*. Dark Horse Books, 2018.
- [14] J. Hickman and N. Spencer, *Infinity*. Marvel Worldwide, Inc., 2014.
- [15] M. Satrapi, *Persepolis*. Pantheon, 2004.
- [16] A. Doxiadis and C. Papadimitriou, *Logicomix: An Epic Search For Truth*. Bloomsbury, 2009.
- [17] N. Gaiman, *Marvel 1602*. Marvel Characters, Inc., 2010.
- [18] W. Ellis, *The Planetary Omnibus*. DC Comics, 2014.
- [19] G. Pak, *Incredible Hulk: Planet Hulk*. Marvel Characters, Inc., 2008.
- [20] J. Hickman, *Secret Wars*. Marvel Worldwide, Inc., 2016.
- [21] J. Fetter-Worm, *Trinity: A Graphic History of the First Atomic Bomb*. Hill and Wang, 2012.
- [22] M. Farinella, *Neurocomic*. Nobrow Press, 2014.
- [23] C. Soule, *Strange Attractors*. BOOM! Studios, 2017.
- [24] S. E. Tabachnick, Ed., *Teaching the Graphic Novel*. New York: Modern Language Association of America, 2009.
- [25] J. G. Nichols, "Hero and the Holocaust: Graphic Novels in the Undergraduate Classroom," in *Teaching the Graphic Novel*, S. E. Tabachnick, Ed. New York: Modern Language Association of America, 2009, pp. 238–244.
- [26] R. Garris, R. Ahlers, and J. E. Driskell, "Games, Motivation, and Learning: A Research and Practice Model," *Simul. Gaming*, vol. 33, no. 4, pp. 441–467, Dec. 2002.
- [27] A. T. Corbett and J. R. Anderson, "Knowledge tracing: Modeling the acquisition of procedural knowledge," *User Model. User-Adapt. Interact.*, vol. 4, no. 4, pp. 253–278, 1994.
- [28] R. Duit and D. F. Treagust, "Conceptual change: A powerful framework for improving science teaching and learning," *Int. J. Sci. Educ.*, vol. 25, no. 6, pp. 671–688, Jun. 2003.
- [29] L. M. Tyson, G. J. Venville, A. G. Harrison, and D. F. Treagust, "A Multidimensional Framework for Interpreting Conceptual Change Events in the Classroom," *Sci. Educ.*, vol. 81, no. 4, pp. 387–404, 1997.

- [30] R. M.-C. Williams, "Image, Text, and Story: Comics and Graphic Novels in the Classroom," *Art Educ.*, pp. 13–19, Nov. 2008.
- [31] P. E. Griffith, "Graphic novels in the secondary classroom and school libraries," *J. Adolesc. Adult Lit.*, vol. 54, no. 3, pp. 181–189, 2010.
- [32] M. Oshii, *Ghost in the Shell*. Palm Pictures, 1998.
- [33] H. Miyazaki, *Spirited Away*. Studio Ghibli, 2001.
- [34] I. Takahata, *Grave of the Fireflies*. Studio Ghibli, 1994.
- [35] R. E. Mayer, "Applying the science of learning to medical education: Applying the science of learning," *Med. Educ.*, vol. 44, no. 6, pp. 543–549, Jun. 2010.
- [36] R. E. Mayer, "Multimedia learning: Are we asking the right questions?," *Educ. Psychol.*, vol. 32, no. 1, pp. 1–19, Jan. 1997.
- [37] D. Hicks, "Chapter 2 Discourse, Learning, and Teaching," *Rev. Res. Educ.*, vol. 21, no. 1, pp. 49–95, 1995.
- [38] E. Michael Nussbaum, "Collaborative discourse, argumentation, and learning: Preface and literature review," *Contemp. Educ. Psychol.*, vol. 33, no. 3, pp. 345–359, Jul. 2008.
- [39] E. M. Nussbaum, G. M. Sinatra, and A. Poliquin, "Role of Epistemic Beliefs and Scientific Argumentation in Science Learning," *Int. J. Sci. Educ.*, vol. 30, no. 15, pp. 1977–1999, Dec. 2008.
- [40] R. K. Atkinson, S. J. Derry, A. Renkl, and D. Wortham, "Learning from examples: Instructional principles from the worked examples research," *Rev. Educ. Res.*, vol. 70, no. 2, pp. 181–214, 2000.
- [41] J. Tuminaro and E. F. Redish, "Elements of a cognitive model of physics problem solving: Epistemic games," *Phys. Rev. Spec. Top. - Phys. Educ. Res.*, vol. 3, no. 2, Jul. 2007.
- [42] A. A. DiSessa, "Knowledge in Pieces," in *Constructivism in the Computer Age*, G. Forman and P. B. Pufall, Eds. New Jersey: Lawrence Erlbaum Associates, Inc., 1988.
- [43] E. Yackel and P. Cobb, "Sociomathematical Norms, Argumentation, and Autonomy in Mathematics," *J. Res. Math. Educ.*, vol. 27, no. 4, p. 458, Jul. 1996.
- [44] K. Tatsis and E. Koleza, "Social and socio-mathematical norms in collaborative problem-solving," *Eur. J. Teach. Educ.*, vol. 31, no. 1, pp. 89–100, Feb. 2008.
- [45] T. J. Bing and E. F. Redish, "Analyzing problem solving using math in physics: Epistemological framing via warrants," *Phys. Rev. Spec. Top. - Phys. Educ. Res.*, vol. 5, no. 2, Dec. 2009.
- [46] F. Jeppsson, J. Haglund, T. G. Amin, and H. Strömdahl, "Exploring the Use of Conceptual Metaphors in Solving Problems on Entropy," *J. Learn. Sci.*, vol. 22, no. 1, pp. 70–120, Jan. 2013.
- [47] T. G. Amin, "Conceptual Metaphor Meets Conceptual Change," *Hum. Dev.*, vol. 52, no. 3, pp. 165–197, 2009.
- [48] J. Osborne, "Arguing to Learn in Science: The Role of Collaborative, Critical Discourse," *Science*, vol. 328, no. 5977, pp. 463–466, Apr. 2010.
- [49] D. Hammer, "Two approaches to learning physics," *Phys. Teach.*, vol. 27, no. 9, pp. 664–670, Dec. 1989.
- [50] D. E. Meltzer, "Investigation of student learning in thermodynamics and implications for instruction in chemistry and engineering," in *2006 Physics Education Research Conference*, 2007, vol. 883, pp. 38–41.
- [51] B. A. Danielak, A. Gupta, and A. Elby, "Marginalized Identities of Sense-Makers: Reframing Engineering Student Retention: Marginalized Identities of Sense-Makers," *J. Eng. Educ.*, vol. 103, no. 1, pp. 8–44, Jan. 2014.

- [52] D. Kuhn and W. Goh, "Technology-Supported Dialog as a Bridge to Developing Individual Argumentive Thinking and Writing," p. 4, 2016.
- [53] P. Brusilovsky, "Adaptive hypermedia: From intelligent tutoring systems to web-based education," in *International Conference on Intelligent Tutoring Systems*, 2000, pp. 1–7.
- [54] P. Johanes and L. Lagerstrom, "Adaptive Learning: The Premise, Promise, and Pitfalls," in *Proceedings of the 124th ASEE Annual Conference and Exposition*, Columbus, Ohio, 2017.