# A Framework for the Design, Production, and Evaluation of Scientific Visualizations

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Ke Er Zhang, Shehryar Saharan, Gaël McGill, and Jodie Jenkinson

**Abstract**

Visualizations play a critical role in discovering, understanding, interpreting, synthesizing, and communicating scientific knowledge. Effective scientific visualization requires careful attention to a number of factors, in particular, a faithful translation of scientific evidence, understanding of the communication needs of the target audience, and skillful application of visualization design principles. As a result, science visualization projects require a team of contributors with specialized knowledge and technical expertise. Regardless of team size and structure, a clear definition and appreciation of the design process as well as an understanding of the responsibilities of each contributor are imperative to the success of a project. Gaps in understanding often result in conflict between visualizers and stakeholders, compromising the quality of the scientific visualization.

Although many companies have developed their own process through trial and error over years of experience, to date, there is no formalized framework for scientific visualization that details the steps of the process and the contributions of each individual. Informed by our examination of case studies, frameworks, and our collective experience as practitioners, we propose a framework tailored to the design, production, and evaluation of scientific visualization that aims to support practitioners in

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meeting their objectives and facilitating conversations that allow others to better understand the impact of the design process on the final product. We explore underlying drivers of decision-making within the visualization design space, describe the activities and outputs that impact decisions made about the final visualization, and discuss potential applications and limitations of this framework in practice.

**Keywords**

Scientific visualization · Multimedia production · Framework · Design process · Design decisions

## 7.1 Introduction

Visualizations (illustrations, three-dimensional models, animations, simulations, multimedia, etc.) play a critical role in discovering, understanding, interpreting, synthesizing, and communicating scientific knowledge (Evagorou et al. 2015; Goodsell and Jenkinson 2018; Lynch 2006; McGill 2022; Reilly and Ingber 2017). An integral part of the scientific process, visualizations contribute to conceptual understanding, scientific reasoning, and knowledge discovery. In addition, visualization plays an essential role in science education (Schönborn and Anderson 2006) both formally and informally, and in public outreach (Trumbo 1999).

Whatever the goal or intended target audience, communication is critical to the research enterprise and a central component in fostering trust within the scientific community (Evagarou et al. 2015). In the age of digital communication, scientific visualization has played an increasingly large role in translating scientific findings for the general public and building trust between science and society (Roche et al. 2021). From beautiful imagery of never-before-seen phenomena to detailed representations and animated narratives, visualization has become commonplace in popular culture and has a pervasive influence on the public's awareness of science (Bucchi and Saracino 2016; Landau et al. 2008).

When we consider the components of a successful visualization, at its core is clear and faithful translation of scientific evidence accompanied by an understanding of the communication needs of the intended target audience (Torsani et al. 2020). These components are intrinsically linked, with the success of one wholly dependent upon the other. Effective visualization is also contingent upon shared understanding of communication goals as well as the process underlying the development of visualizations. A gap in understanding can result in conflict, miscommunication, and/or lack of trust between visualizers, stakeholders, and other project partners (McGill 2017). This can compromise the quality of the scientific visualization and ability of the final product to serve the needs of the target audience.

The design of visualizations may involve a team of one or it may require a large, interdisciplinary team of researchers, visualizers, developers, user experience (UX) and user interface (UI) designers, evaluators, subject matter experts, and managers facilitating interactions between all parties. Regardless of team structure, a clear definition and appreciation of the design process as well as an understanding of the responsibilities of each contributor is imperative to the success of the project. Although many groups and companies have developed their own process through trial and error over years of experience with scientific visualization, to date, there is no formalized framework for scientific visualization that establishes the steps of the visualization process and the contributions of each individual.

In this chapter, we review scientific visualization case studies that span a number of modalities and contexts-of-use, and examine a number of frameworks related to the design of visualizations. We explore the many underlying drivers of decision-making within the visualization design space, and how activities and outputs created throughout the design process impact decisions made about the final visualization. Informed by our examination of case studies, frameworks, and our collective experience as practitioners, we propose a framework tailored to the design, production, and evaluation of scientific visualizations and detail the benefits and challenges experienced at each step of the visualization process. Finally, we discuss the potential applications and limitations of this framework in practice.

## 7.2 Analysis of Existing Visualization Processes

### 7.2.1 Case Studies

We present a selection of case studies that provide an overview of the scientific visualization landscape and reveal a variety of factors that drive decisions behind the design of visualizations. These case studies cover a wide range of contexts and come from our own experiences working in these spaces, featuring projects with different visualization goals, subject matter, clients, target audiences, design styles, media types, and venues. While many of these cases have successful outcomes, they also highlight the challenges faced by visualizers and their collaborators when one or more steps of the design process do not go as planned. By examining these case studies, readers can gain a better understanding of the intricacies involved in creating scientific visualizations.

#### 7.2.1.1 Visualization for Academic Research Communications

The production of didactic illustrations for academic publication or presentation is a frequently assigned task for scientific visualizers. This case study examines an illustration project for an academic research group working on cutting-edge research, developing biodegradable and biocompatible polymers for biomedical applications. The research group (client) contracted a scientific visualizer who was tasked with creating a visualization that highlighted the use of injectable biodegradable polymers for treating critical limb ischemia through local pro-angiogenic peptide delivery. The main goal of this visualization was to communicate the research of the academic lab in a more accessible and efficient way to scientists within this field and adjacent fields. Although its primary context-of-use was in an academic research publication, it was also meant to be used in formal audio-visual presentations.

From the outset of the project, there was clear and open communication with the client regarding their specific expectations. The client appointed a researcher to liaise with the scientific visualizer and represent the interests of the research group. The first step of the project included the creation of a collaborative and living document outlining the research content and scope of the project. This document allowed the visualizer and client to collaborate on content, initial treatment possibilities (including fidelity of the end product), and collect existing visual media to build a landscape of the field and identify standards for visually encoding information early in the project. This initial step clarified the project expectations, scope, and goals for all stakeholders, laying a solid foundation for the remainder of the project.

After the visualizer created several thumbnails, the most successful concepts were selected and presented to the client. The client was highly responsive and engaged, providing suggestions for the concept and feedback regarding scientific accuracy. Once a concept was selected, the visualizer created a comprehensive draft, which was refined over several rounds of iterative feedback. The client was again highly involved and looped in team members to review the visualization for its accuracy as well as its effectiveness in communicating the content. Once both parties were confident in moving forward, the design was "locked in," and the production of the final visualization began. Thanks to the collaborative and iterative refinement that took place at the beginning of the project, the production phase proceeded exceptionally smoothly. The only revisions made during this step were edits to the copy. The project was deemed successfully completed once the visualization was approved and the final files were delivered to the client (see Fig. 7.1). This success was largely due to the strong partnership and trust between the

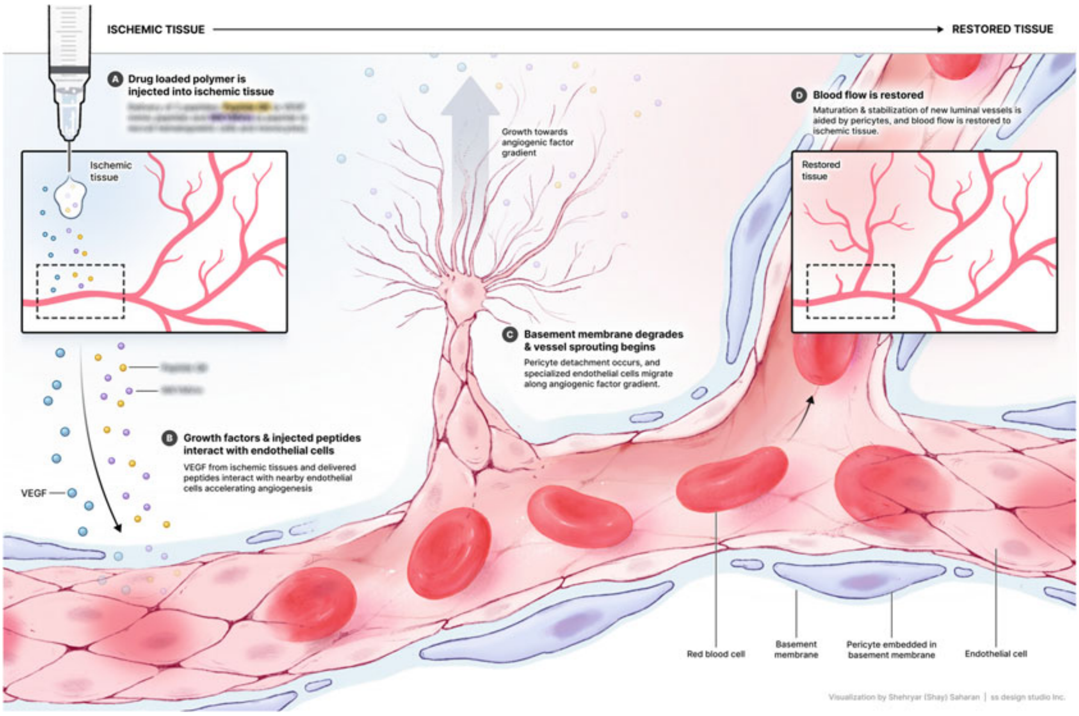


**Fig. 7.1** Final illustration for an academic research group developing biodegradable and biocompatible polymers for biomedical applications. Copyright 2023 by ss design studio Inc. Reprinted with permission

visualizer and the client, fostered through consistent collaboration, communication, and engagement. By investing time and effort to achieve alignment at the outset of the project, both the client and visualizer set the stage for a smooth execution of the project. However, due to resource-related constraints, the final visualization was not tested with the target audience to assess if it met its communication goals.

#### 7.2.1.2 Visualization for Biotechnology and Pharmaceutical Marketing and Communications

One of the primary markets for the creation of commission scientific animations is the biotechnology, pharmaceutical, and medical device industry. Projects in this space often fall into a few common categories: mechanism of action animations, product launch animations, and animations for internal training, education, and onboarding. Depending on the size of the biotechnology or pharmaceutical company, scientific designers/animators may either interact with the marketing and communications team (for larger, more mature companies) or with C-level executives (and even CEOs, in the case of earlier-stage companies). It is also common for scientists from the research and development department to be brought into the process for early-stage conceptualization and review. The following case study represents a rather typical and successful path through the process of scientific animation development by a team of scientific visualizers, where, despite the client having a clear idea of the key messages and visuals needed to communicate to their target audience, the visualization design team still navigated the full pre-production and production phases to arrive at a finished animation.

Fenix Health Sciences is a nutritional supplement company that develops a lipid formulation to address nutritional deficiencies associated with inattention and emotional dysregulation. The visualization team worked directly with the

CEO, who gave the team a series of preliminary storyboard outlines at the start of the project. This was seen as unusual because many clients do not necessarily take steps in advance to "think visually" and develop a progression of events they want to see onscreen, even if it is only captured as a text document. Although the storyboards and eventually the final animation were substantially different from these initial drafts, creating preliminary outlines placed the client in a frame of mind suited to visual thinking and raised their awareness of the design and visual storytelling process.

As part of this project, the visualization team created "story beats" before launching into the storyboarding process; these story beats are representative sketches associated with a particular segment of an animation. While storyboard frames follow the pace of the narration script and offer detailed representations of individual shots (a "shot" is a continuous sequence of images that shows a specific action or scene in an animation or film), story beats have a different purpose. Rather than being directly linked to the script, story beats serve as early visual explorations of the kinds of environments that could be useful in conveying the client's story before one has reached the storyboarding stage. After collaborating on the narration script, which was initially drafted by the client and further refined by the visualization team, the team created storyboards that could visually capture the overall story. At this stage, color was incorporated into the storyboards since it played an important role in communicating specific aspects of the science, such as the variety of structural components in various families of membrane lipids in cells; typically, color is explored at later phases of the visualization process, such as in the "mood board" development phase. Once the storyboards were finalized, the visualization team explored a suitable representation style for the molecules featured throughout the animation before launching into the 3D production phase of the project. At this stage, they created complex molecular models and simulations of dynamic cellular membranes, the accuracy of which was guaranteed by scientists on the visualization design team with the corresponding expertise (i.e., PhD-scientists who had worked on such modeling and simulation tasks as part of their research theses).

Overall, this exemplified a *"successful"* development process, where navigating the pre-production and production phases proceeded smoothly with the client. By leveraging the different outputs created throughout the pre-production phase (see Fig. 7.2 for script, story beats, storyboards, preliminary 3D models), the visualization team avoided unforeseen changes in story direction and shifts in stylistic approach.

#### 7.2.1.3 Visualization for Formal Education

Unlike visualizations for corporate marketing and communication clients, projects in the formal education space are driven by a different set of design priorities. In the former, decisions often center around the client's desire to tell a compelling story and engage the audience—in this context, it is not uncommon for issues of scientific accuracy to clash with the narrative goals. Although these issues can be reconciled with careful scientific and design discussions, storytelling lies at the heart of the project's design mandate and becomes the driving force for many subsequent decisions. In contrast, formal education projects prioritize *learning objectives* as the principal driver of all decisions throughout the project. These pedagogical goals become the central organizational pillars around which media types (e.g., static figures, animations, interactive tools) and design styles (e.g., simple, diagrammatic 2D artwork versus immersive 3D content) are chosen, especially in the development of highly structured curricular products by the publishing industry (e.g., textbooks and their supplemental digital materials). Although many of the stakeholders—including authors, editors, curriculum designers, assessment specialists, and platform programmers—share an overarching goal of increasing learning gains for students, there is often confusion and poor management in the process necessary to achieve these goals.

Historically, in the textbook publishing industry, authors drive the creation of text content early

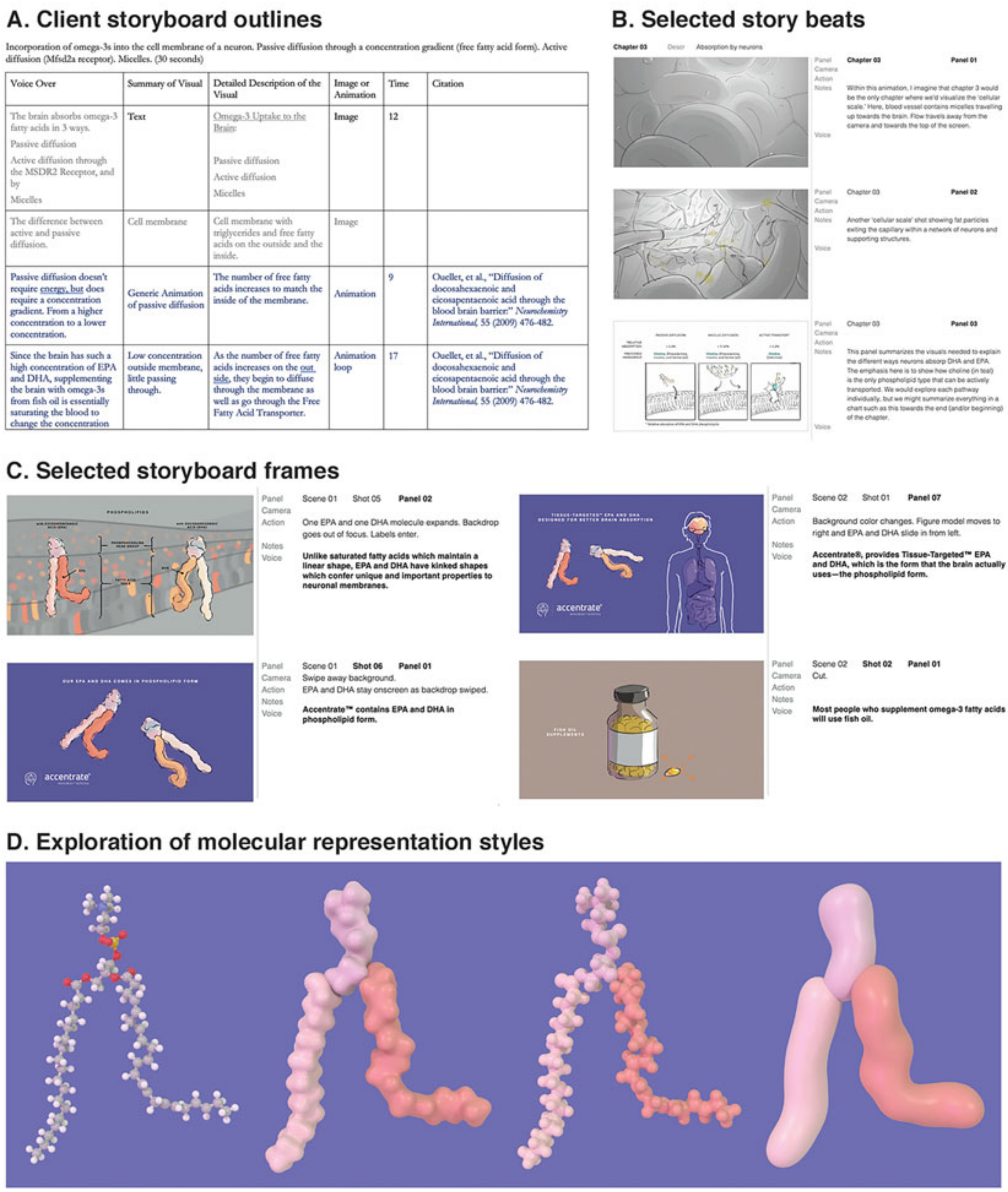


**Fig. 7.2** Pre-production materials (outlines (**a**), story beats (**b**), storyboard frames (**c**), style exploration (**d**)) for a 3D animation for Fenix Health Sciences. Copyright 2022 by Digizyme Inc. Reprinted with permission

on in the process and treat visual media as an afterthought secondary to the text. In the best of cases, editors recruit artists with scientific training to produce static imagery and to provide guidance on the strategic use of visuals, though this depends on their level of collaboration with the authors. However, the advent of digital platforms (e.g., eBooks, online learning systems to host textbook supplements) has expanded the range of educational multimedia beyond static images and figures. These new types of multimedia, such as animations and interactive tools, require a more complex process to develop than the traditional, diagrammatic art found in print textbooks; unfortunately, this is where the publishing industry has lagged in its understanding and ability to innovate. For example, it is not uncommon for educators to be recruited on a contractual basis to ideate storyboards for educational animations, despite the fact that they are not trained in the design of animated media and may not possess the graphical skills to capture their ideas effectively. These storyboards are reviewed by a different set of educators who, again, provide feedback without context or experience in the process of multimedia production. Authors can sometimes remain divorced from early ideation phases, and they are only brought in to review design concepts when it is too late to adjust course.

Conversely, working with scientifically trained visualizers provides a competitive advantage in the development of successful pedagogical media for textbooks and classrooms. These practitioners are able to engage authors at the earliest stages of the ideation process and leverage their skills to design clear storyboards that fulfill pedagogical goals, as seen in Fig. 7.3. This approach avoids the loss of important pedagogical and engagement opportunities that can result from following an ill-informed design process. Overall, a well-organized pipeline is one of the key foundational elements that designers can introduce at the start of a project to establish a productive working relationship with publishers and their authors.

#### 7.2.1.4 Visualization for Health Policy and Communications

Thus far, our case studies illustrated the role that narratives and pedagogical goals play in influencing a scientific visualizer's design decisions. In this case study, we highlight the influence clients and audiences can have on the visualization process. One such area is in health policy and communications. Public health agencies, focused on maintaining and improving the physical and mental health of its citizens, employ graphic designers to create visualizations that facilitate communication between policy workers (clients) and senior policy decision-makers (audience), for instance, in the pitching for or proposing of public health initiatives. This requires designers to communicate a mix of conceptual ideas (e.g., the vision of a future healthcare system) and concrete evidence (e.g., current data on a public health topic) while also leaving a strong impression on their audience in a limited amount of time. Scientific visualizers excel at creating visual syntheses that tie various

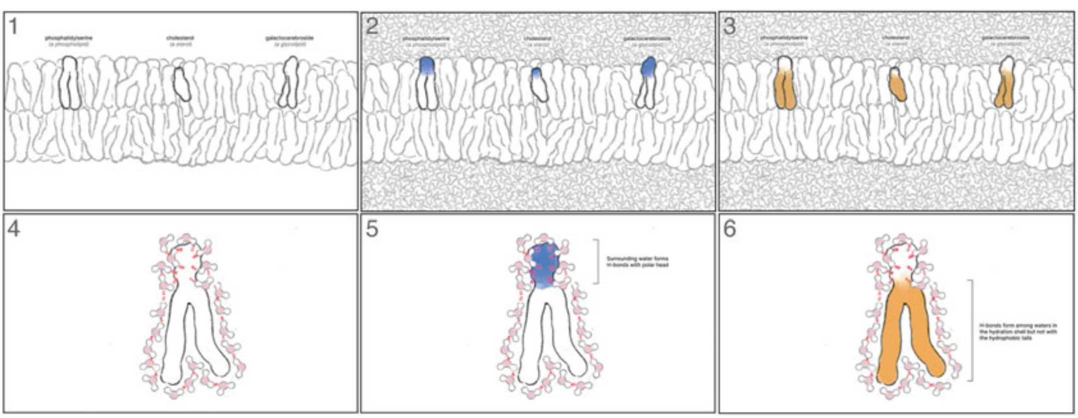


**Fig. 7.3** Selected storyboard frames crafted by a scientifically trained artist who collaborated closely with a textbook author team to develop a visual sequence that caters to chosen learning objectives. Copyright 2023 by Digizyme Inc. Reprinted with permission

streams of information together, showing what these ideas could look like as tangible products—for example, creating static mock-ups of an interactive tool that visualizes environmental health indicators.

An in-house designer within the government agency is usually brought onto a project that already has a reasonably well-developed narrative crafted by a client team consisting of content writers and/or subject matter experts (e.g., epidemiologists, policy analysts). In the initial consultation, the designer assesses the needs of their client and translates their request into a set of design requirements. Since it is important for clients to actively engage their audience (e.g., senior decision-makers), the designer and client will often make design decisions together. For example, the designer may capture their design recommendations (e.g., design decisions, content structure, design approach, style inspiration) in a design brief and hand this over to their client—this gives the client the ability to contribute to the overall structure and esthetic of the final product so that it can better engage their audience. These briefs also help designers familiarize clients new to the design process and clarify expectations.

Projects progress more smoothly when designers and clients communicate effectively during the initial consultation and collaborate on pre-visualization materials. These are all opportunities to make sense of the project, with designers and clients sharing a common understanding at the end of these activities. Challenges, on the other hand, arise due to different decision-making approaches, time pressures, and varying levels of awareness of the visualization process. Top-down decision-making is not uncommon in governmental bodies; but when it occurs at the eleventh hour, it leads to changes in content and design during late stages where projects tend to be less editable. These changes in direction occur especially when the client and the visualization team are misaligned throughout the project and have different interpretations of the project requirements. Although review sessions are scheduled into the project plan to prevent these complications, these sessions may be overlooked due to time constraints. In situations where there is bottom-up rather than top-down decision-making, "design by committee" can occur; this translates to rounds of review sessions where most of the feedback is integrated equally into the final product. Oftentimes, this feedback can come from individuals without a background in design or visualization. This can lead the process down a path of well-intentioned but ill-informed decisions, creating a "Frankenstein-esque" product that is unable to serve its specific visualization goals.

#### 7.2.1.5 Visualizations for Public Education

Science museums are wonderful venues for informal science education and often require the expertise of scientific visualization designers and animators to support their exhibit development goals. There is a great variety of work that results from these projects since museums innovate new forms of engagement for the public and often integrate both physical and digital exhibit components. In the following case studies, we detail the typical design process for museums that work with in-house exhibition designers (e.g., content writers, visualization designers, fabricators) as well as third-party collaborators.

##### 7.2.1.5.1 Ontario Science Center: Vaccine Awareness Exhibit

The Ontario Science Center (OSC) is a science and technology museum located in Toronto, Canada, catering primarily to families with children, as well as educators and their students. The OSC employs a collaborative and non-linear, iterative design methodology in the production of a wide range of media (including static, animated, and interactive media), primarily designed for in-person exhibitions. The OSC often creates exhibits that are highly visual and interactive, with the goal of "showing before telling" to engage the audience.

The process begins with a team of designers, science writers, educators, and science researchers working together to identify the content objectives and target audiences of their visual media. A wide environmental scan is conducted to gain a better understanding of the subject area and scope of the project. Test groups (focus groups) are sometimes used to narrow potential topic areas. Once key points and messages are identified, the team begins to think about the different types of experiences they can potentially craft. This includes deciding on the best approach based on the type of information being communicated and how it will be presented. Once a design direction is set, the team begins to think more specifically about the details—for example, determining a balance between written and visual content such that it is suitable and interesting for a wide range of visitors that may enter the exhibit. This also includes building a detailed content inventory to identify and document assets needed for production. The final product is then built and tested with museum visitors in order to identify and iterate on areas of improvement.

An example of a current and ongoing OSC project is a new *Vaccine Awareness* exhibit about the science of vaccines and immunity. The project includes a physical exhibit and accompanying digital content, available on the exhibition floor and to other educational institutions online. The project team is large in size, with multidisciplinary members that draw expertise from a variety of domains such as science research, scientific writing, 2D and 3D media design, electronics, software development, project management, sponsorship, marketing, education, and evaluation. Clear communication is key to a positive working experience, especially in a project of this scale and complexity. OSC has achieved this through clearly outlining project objectives, documenting and constantly reflecting on a predetermined design methodology, delineating the roles and responsibilities of each contributor, and identifying liaisons from each domain. Some recurring problems in past projects resulted in steps taking longer than expected (e.g., contributors may be resistant to handing off materials before they are perfected), and the project team not communicating expectations and timelines with peripheral stakeholders (e.g., marketing) at an earlier stage of the project. These issues, if not addressed immediately, may lead to the addition of unexpected tasks, revisions of completed work, and ultimately delays throughout the project timeline. Project managers may schedule regular check-ins and weekly team meetings to avoid potentially costly revisions and additional work in a new project.

##### 7.2.1.5.2 Nobel Prize Museum: *Life Eternal* Interactive Exhibit

As part of an exhibit at the Nobel Prize Museum (Stockholm, Sweden) on longevity that features Nobel Prize winning discoveries, the museum team collaborated with a scientific visualization company and an outside exhibit design team to create a kiosk experience. The project leveraged the Unity game engine software platform to build the user interface and let visitors select from four Nobel discoveries—Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), Telomeres, Pluripotent Stem Cells, and Autophagy—and learn how each relates to the exhibit title, *Life Eternal* (see Fig. 7.4).

This project exemplified a situation where project review and collaboration can occur not only with a client, but also with a third-party collaborating design firm. While it is generally beneficial to involve another team of visual professionals for their expertise and creativity, it may also impact the pre-production and production processes by introducing additional viewpoints that must be thoughtfully incorporated. The scientific visualization team was given the responsibility to select scientific narratives as well as determine the appropriate level of detail and accuracy with which to depict them, and thus they developed storyboards that they believed included adequate scientific context to orient a general audience visiting the exhibit. However, the initial response to these storyboards was to increase the level of interactivity for the visitor and reduce the expository scientific content. This advice was based on the collaborating design firm's overall experience with museum exhibit design, but it was one devoid of experience with the communication of challenging scientific topics. Although the storyboards were modified to immerse visitors into interactive activities as suggested (and this direction was

**Fig. 7.4** *Life Eternal* Nobel Museum exhibit in Stockholm (top panel) for which a series of science education exploratory modules related to Nobel-winning discoveries were created in the Unity game engine (bottom four panels). Copyright 2022 by The Nobel Prize Museum. Reprinted with permission

followed for the rest of the project's pre-production and production phases), it was acknowledged in hindsight that the scientific visualization team's original suggestion to provide a stronger scientific background was a better one!

It is challenging to know when and how to relinquish important design decisions, especially if one perceives that the client or third-party design group has more experience in a certain design space. The realm of scientific visualization is rather unique in that our training prepares us to be attuned to the right balance of esthetic and veridical experiences for viewers. While another collaborating group may specialize in a particular design space or mode of delivery, the challenge of conveying complex scientific concepts to an audience oftentimes takes precedence over other areas of expertise, and prioritizing the audience's needs becomes the first and foremost consideration from which all other design decisions should flow.

#### 7.2.1.5.3 Science Documentary Films

Science documentary films are a less common type of project that nonetheless leverages the skills of the scientific visualization community. These projects often involve working with a film director and sometimes a funding entity that commissions the film. This case study details the challenges inherent with this medium and the difficulties of integrating into the typical workflow of documentary filmmakers. The film in question focused on the human microbiome and aimed to help general audiences appreciate the ubiquitous role that bacteria play in human development. It contrasted these themes with the common assumption that these microorganisms are mostly detrimental to human health and at the root of many illnesses. Although the project was funded by a probiotics company, the CEO and executives communicated clearly from the outset that they did not want this film to feel like a corporate advertisement; instead, it should be a public education effort that broadly raises awareness about the human microbiome. The film director, an experienced artist who was sensitive to the nuances of the science throughout, was not a scientist by training and relied heavily on the client and the scientific visualization team's expertise—in fact, a central thread of the film became the "behind-the-scenes" creation process of the very visualizations produced. Despite this interesting and flattering turn of events, the visualization team experienced serious misalignment issues while collaborating on this project—issues that they soon realized were inherent to the creative journey by which documentary films are produced.

Many documentary filmmakers have a fluid process that begins with an idea or a set of questions that propels their research and determines the initial footage they plan to shoot and include in the film. They begin the project exploratively with the understanding that the shape and even overarching theme of their film can shift significantly as they learn about their topic and discover unexpected human stories during filming. As such, much of the key creative decisions that result in the "final cut" can take place at the eleventh hour in the editing room rather than at the start of a project. Although this approach gives filmmakers maximum flexibility to discover the most compelling version of the story, it sharply contrasts the level of planning and certainty required in scientific visualization projects; in the latter case, a significant amount of time is often invested during pre-production to increase clarity and a smooth production process in later stages of the project. In this case study, the visualization team came to realize their storyboards served more as a tool to educate the filmmaker about interesting aspects of the scientific story rather than as final visual sequences to create. Instead of developing storyboard ideas that matched an existing script, the team wrote a script that accompanied and explained the storyboard to the film director and client. As the director continued to refine successive "rough cuts" of the documentary, the storyboard sequence was similarly trimmed and rearranged as modular pieces of the scientific story. After much flexibility in unfolding of the creative process (i.e., the concomitant flexibility in deadlines), the final shot list was "locked" from further tweaks so that the visualization team could focus on production.

Ultimately, this project demonstrated a seamless integration of scientific knowledge and artistic expression, made possible by a high degree of openness and trust between the visualization team and the film director. The director relied on the scientific expertise and feedback provided by the visualization team to shape the final story arc (i.e., story sequence), and the visualization team relied on the director's creative vision to craft an engaging film that remained faithful to the science.

#### 7.2.1.6 Visualization for Knowledge Discovery

Unlike projects where the story and/or learning objectives are the primary factors influencing visualization decisions, knowledge discovery projects are driven by the need to enable scientists and collaborators to make sense of data—the data themselves *are* the story. The priority becomes the development of visual methods and representational styles that support a more open-ended exploration and experimentation with the visualized data. Since it is not yet clear what findings and epiphanies will emerge from inspecting the visualized data—whether they are more abstract, quantitative data sets or ones based on three-dimensional structural features at molecular, cellular, anatomical, or other scales—it is critical for the visualizer to work closely with scientists to gauge the usability of the visualization and how users' interaction with it may evolve over time. Unlike story-driven projects where it is important to "lock down" the visual treatment (cinematic and stylistic aspects of the project) early on to protect it from changes that may appear during production, knowledge discovery projects begin with the assumption that the approach to visualizing the data must remain flexible enough as users continue to experiment with the visualized dataset and, hopefully, learn to inspect and derive new insights from these data.

Another key feature of specific knowledge discovery projects is that they encourage the integration of multiple types of data within a common visual environment. A visualization in this case may be the first time that disparate datasets (i.e., ones coming from different kinds of instruments or addressing different characteristics of a biological structure or process) are brought together and merged in order to derive novel observations. This approach is exemplified in a recent project that aimed to create a continuous visual model of the SARS CoV-2 spike-induced membrane fusion process. Visualizing this process required that numerous datasets (structural and dynamic) from multiple fields (X-ray crystallography, nuclear magnetic resonance, cryo-electron microscopy and tomography, circular dichroism, and microscopy) be combined into a cohesive, dynamic model. This visual model was then used for both conceptual and communication purposes—(a) it helped collaborating researchers form an improved mental model of this 3D process and a better understanding of the mechanism of action of their spike-targeted peptide inhibitors, (b) helped reviewers understand the research during the peer-review process and, ultimately, (c) allowed readers to understand the context of the therapeutic intervention (de Vries et al. 2021; see Fig. 7.5).

It was particularly rewarding when the hypothesized intermediates of the viral spike—i.e., the protein conformations that resulted from the careful modeling, rigging, and simulation stages of the visualization process—were later found to be in agreement with a follow-up cryo-electron tomography study (Marcink et al. 2022). Other scientist-practitioners have described similar uses of visualization (Iwasa 2010; McGill 2022), which emphasizes the value and importance of building scientifically accurate models that allow users to freely explore the data and create alternate versions of the model. Visualizations in this case serve as the basis for *in silico* experimentation and exploration, as opposed to only tools for communication and engagement.

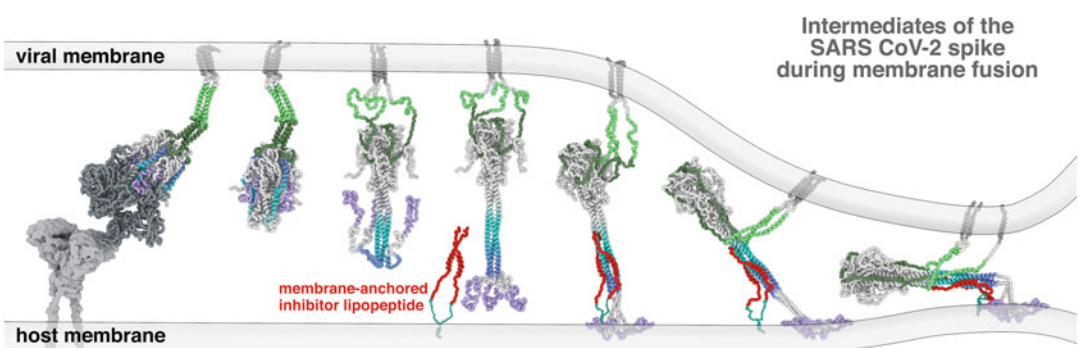


**Fig. 7.5** Example of a figure derived from a knowledge discovery project modeling and simulating the intermediate conformations of the SARS CoV-2 spike during membrane fusion. Copyright 2022 by Digizyme Inc. Reprinted with permission

### 7.2.2 Analyzing Visualization Workflows in Practice

#### 7.2.2.1 Decision-Making Between Visualizers, Clients, and Their Collaborators

All of the case studies described above reinforce our understanding of the key components that contribute to a successful visualization—in particular, an accurate representation of scientific evidence and a shared understanding of visualization goals between visualizers, clients, and their collaborators. These case studies give further insight into the dynamics of the interactions between these groups, especially how they interact with one another and influence design decisions. It is clear that clients and peripheral collaborators wield considerable influence over decisions about the final product as well as the design process. A few of our cases show how changes in direction from clients and collaborators, especially at the eleventh hour, can drastically change the outcome of the final product at the cost of additional stress to scientific visualizers, delays to the project timeline, and revisions to already completed work. In situations where decision-makers are not experienced in scientific visualization nor its process, these case studies demonstrate a need for clients and collaborators to trust visualizers to make informed decisions as trained experts in scientific storytelling and provide timely input on outputs (e.g., comprehensive drafts, storyboards, design briefs) throughout the design process that are meant to maintain common ground between visualizers, clients, and collaborators. Conversely, visualizers should also take the initiative to familiarize clients with respect to the collaborative design process.

#### 7.2.2.2 Design Process Dictated by Project Requirements

Additionally, these case studies illustrate how the design process is a flexible one that is shaped and molded by project requirements such as visualization goals, media type, and context-of-use. These factors affect the steps to be included or excluded in a workflow, time and importance allocated to each step, and overall flexibility in the workflow. In situations where the visualization goal is open-ended (e.g., knowledge discovery), visualizers develop highly flexible techniques and workflows that allow data exploration and serendipitous discoveries. Conversely, in situations where the goal is more defined (e.g., marketing communications), projects are scoped early on in the design process, and the degree of editability diminishes throughout the process so as to push the project to its finish line. Therefore, it is important for visualizers, clients, and collaborators to clarify and mutually agree upon project requirements near the start of the project, to ensure the development of a workflow that can effectively fulfill those requirements.

### 7.2.3 Analyzing Conceptual Frameworks for Visualization Design Processes

To further contextualize our work, we examined conceptual frameworks related to the design, production, or evaluation of visualizations. The author team drew from their personal knowledge and experience in various fields to identify existing frameworks that are commonly used and cited in scientific visualization and visualization-adjacent fields—this was a selection of seven frameworks in product design, instructional design, multimedia production, knowledge translation, and science communication (see Table 7.1 below). We compared these frameworks and highlighted a few traits that are common among the different perspectives and approaches to visualization projects.

#### 7.2.3.1 Phased Approach

Many of these frameworks view the overall design process as a phased approach that involves defining a problem at the start of the process and delivering a tailored solution at the end. Each phase consists of steps with actions or activities, where users of the framework must actively perform these steps and activities to progress toward

**Table 7.1** Frameworks, models, and workflows analyzed in the development of our scientific visualization framework

| Framework | Author | Description | Details |
|---|---|---|---|
| ADDIE | Branch (2010) | ADDIE (Analyze, Design, Develop, Implement, and Evaluate) is a phased approach to building effective learning solutions. It is meant for use in intentional learning environments that are student-centered, innovative, authentic, and inspirational. | Five phases:<br>1. Analyze: Identify causes for performance gaps in the learner. Determine instructional goals, target audience, and required resources to deliver the learning solution.<br>2. Design: Design a learning solution that aligns learning objectives and instructional strategies with instructional goals.<br>3. Develop: Generate, validate, and conduct a pilot test for learning resources in development.<br>4. Implement: Implement the learning solution by preparing the learning environment and engaging participants who will interact with learning resources.<br>5. Evaluate: Assess the quality of the learning solution formatively. Assess how successfully the solution meets instructional goals summatively through participant perception, learning, and performance. |
| Systems approach model | Dick and Carey (1978) | This component-based model focuses on the interrelationship between context, content, learning, and instruction in the design process. The instructor, learners, materials, instructional activities, delivery system, and learning work together to produce the desired outcomes. Components of this model are executed iteratively and in parallel with each other. | Ten Components<br>1. Identify instructional goals.<br>2. Conduct instructional analysis.<br>3. Analyze learners and contexts (entry behaviors, learner characteristics).<br>4. Write performance objectives.<br>5. Develop assessment tools (criterion-referenced test items).<br>6. Develop instructional strategies.<br>7. Develop and select instructional materials.<br>8. Develop and conduct formative evaluation.<br>9. Revise instruction.<br>10. Develop and conduct summative evaluation. |
| Design thinking | Stanford d. School (2010) | Design thinking is a methodology (set of cognitive, strategic, and practical procedures) for creative problem-solving. It presents a non-linear, iterative process for designing user-centered solutions. It puts people at the center of the development process and encourages the creation of products that resonate more deeply with an audience. | Five modes:<br>1. Empathize: Understand the needs, actions, beliefs, and values of people within the context of the design challenge.<br>2. Define: Craft a meaningful and actionable problem statement that focuses on the insights and needs of a particular user or composite character.<br>3. Ideate: Generate ideas and defer judgment.<br>4. Prototype: Iterative generation of artifacts that can elicit useful feedback from users and colleagues.<br>5. Test: Solicit feedback about the prototypes from users and gain empathy for them. |

(continued)

**Table 7.1** (continued)

| Framework | Author | Description | Details |
|---|---|---|---|
| Double Diamond | Design Council (2019) | Double Diamond is a design methodology within the British Design Council's framework of innovation that presents a non-linear, iterative process of divergent and convergent thinking. | Four phases:<br>1. Discover: Understand rather than assume what the problem is.<br>2. Define: Use the insights gathered to clearly define the challenge in a new light.<br>3. Develop: Develop different solutions to the defined problem by seeking inspiration and co-designing with diverse perspectives.<br>4. Deliver: Test the different solutions at a small scale, rejecting those that will not work and improving the ones that will. |
| Knowledge-to-action framework | Graham et al. (2006) | A conceptual framework for facilitating the use of research knowledge by various stakeholders. The framework emphasizes collaboration between knowledge producers and knowledge users throughout the process. | Two multiphase components:<br>1. Knowledge creation: Distill knowledge into a tool or product tailored to knowledge users.<br>a. Knowledge Inquiry.<br>b. Knowledge Synthesis.<br>c. Knowledge Tools/Products.<br>d. Tailoring knowledge throughout.<br>2. Action: Bring knowledge into practice or awareness.<br>a. Identify the problem.<br>b. Identify, review, and select knowledge.<br>c. Adapt knowledge to local context.<br>d. Assess barriers to knowledge use.<br>e. Select, tailor, and implement interventions.<br>f. Monitor knowledge use.<br>g. Evaluate outcomes.<br>h. Sustain knowledge use. |
| Animation design workflow | Jantzen et al. (2015) | A typical workflow for the design of 3D computer animations. This three-phase workflow is an iterative process of generation and refinement that balances storytelling with the communication needs of the intended target audience. | Three phases:<br>1. Pre-production: Identify communication objectives, audience, and scope and collect reference material that inform the development of a script. This script is broken down visually into storyboards and paced using an animatic.<br>2. Production: Produce visual assets through activities such as 3D modeling, rigging, animation, dynamics, texturing, lighting, and rendering.<br>3. Post-production: Tie together the different assets generated during production through compositing. The final product is then exported to meet dissemination requirements as specified by the client. |
| Building Science Graphics | Christiansen (2023) | A practical, step-by-step workflow for communicating science through illustrated explanatory diagrams and data visualizations for a variety of venues (e.g., articles, poster presentations, press releases, social media posts). | 28 steps:<br>1. Confirm the need for a graphic.<br>2. Describe the context (outlet, audience, tone).<br>3. Initiate a team list and schedule (active content collaborators, reviewers).<br>4. Shift focus to content.<br>5. State the specific goal of your graphic. |

(continued)

**Table 7.1** (continued)

| Framework | Author | Description | Details |
|---|---|---|---|
| | | | 6. Check-in with collaborators about the goal statement.<br>7. Gather reference material related to the goal statement.<br>8. Read and take notes on the reference materials.<br>9. Revisit your goal in light of reference material.<br>10. Translate writing into sketches.<br>11. Create frames/miniatures of the final graphic.<br>12. Organize information within the miniature frames in an abstract and gestural manner.<br>13. Draw out your favorite miniatures in more detail. Write preliminary captions and annotations.<br>14. Check if the emerging plan aligns with the context and content.<br>15. Create a full-sized concept sketch including preliminary captions and labels.<br>16. Critique the communication value of your own sketch.<br>17. Seek concept sketch feedback from collaborators.<br>18. Digest concept sketch feedback.<br>19. Develop a tight sketch.<br>20. Seek tight sketch feedback from collaborators.<br>21. Digest tight sketch feedback.<br>22. Execute the final graphic.<br>23. Seek a final round of feedback from collaborators.<br>24. Address final notes.<br>25. Write image alternative (alt) text.<br>26. Write an image credit.<br>27. Confirm that your files are ready to print or post.<br>28. Create variations of the same content for different audiences and outlets. |

an end goal. Each phase of the process builds upon the next to improve and refine the solution, and completing these steps in succession ensures a solid foundation for a visualization project.

These frameworks emphasize a shared understanding of project requirements among collaborators and stakeholders at the start of the design process, such as defining realistic visualization goals, target audience(s), medium(s), and venue(s) after a review of the problem space (a “problem space” refers to the entire range of components that define and solve a problem, e.g., history of the problem, stakeholders involved) and available resources. The next phase involves designing and drafting a potential solution, with some frameworks encouraging the development of innovative and creative ideas by deferring judgment (Stanford d.School 2010; Design Council 2019). The visualizer then refines the draft into a final product, and the design process ends when this product is delivered and assessed for its efficacy in meeting the initial visualization goals.

#### 7.2.3.2 Iterative and Non-linear Steps

Most frameworks also describe the design process as one that is iterative and non-linear. This means that visualizers may revisit steps based on feedback from collaborators and other reviewers. For instance, frameworks in product design, instructional design, and knowledge translation (e.g., Stanford d.School 2010; Branch 2010; Graham et al. 2006) ask practitioners to solicit feedback in phases, formatively assessing the quality of their product with experts and users during development (e.g., pilot-testing) and summatively evaluating the effectiveness of the final product. These activities aim to provide creators with a perspective different to their own and to flag errors in the design in order to continuously improve the product as it moves through the design process (Design Council 2019).

#### 7.2.3.3 Context-of-Use

Lastly, the steps in the design process depend on the context in which the product is used. Some frameworks, such as in instructional design, aim to create products that change aspects of the problem space and the target audience (e.g., change student behavior). In such instances, the product serves as a "means to an end" and is most valuable when it helps users achieve specific goals in specific contexts. To ensure this, these frameworks often involve steps that assess the needs of the target audience and evaluate the effectiveness and impact of the product in a given setting.

On the other hand, frameworks, such as in multimedia production and science communication, may see the product as intrinsically valuable. In these cases, the product is valued for both its artistic qualities and in its ability to communicate information across a range of contexts (e.g., an infographic read widely by different audiences). These frameworks emphasize the production process, technical prowess, and iterative feedback between visualizers, clients, and collaborators required to create a product that communicates its intended message.

## 7.3 Development of a Visualization-Specific Framework

Our analysis of both conceptual frameworks and case studies has provided us with a set of features that form the foundation of the scientific visualization framework presented in this chapter. This is a phased approach that is able to account for iterative, non-linear revisions during the design, production, and evaluation of a visual product; an interdependent system of steps, activities, and people, or rather the skills of people, that ensure the selection of and agreement upon design decisions best suited to the project; and lastly, a process that can be adjusted to fit different project requirements with different visualization goals, media types, and contexts-of-use. Below, we propose a tailored, formalized framework that will support scientific visualizers to meet their objectives and facilitate necessary conversations with stakeholders that allow them to better understand the impact of the design process on the final product.

### 7.3.1 An Overview of the Scientific Visualization Framework

The process of creating a successful visualization project involves several phases and steps that should be carefully followed to achieve the desired outcome. The proposed framework follows a non-linear, iterative process and is described in 11 steps that fall under three main phases. The first phase, pre-production, involves gaining a shared understanding of the project requirements by engaging with stakeholders and collaborators, defining project requirements, ideating, creating drafts, and conducting several rounds of review. The second phase, production, involves building data-driven and scientifically accurate assets and compiling them into a preview of the final visualization for feedback and approval. The final phase, post-production,

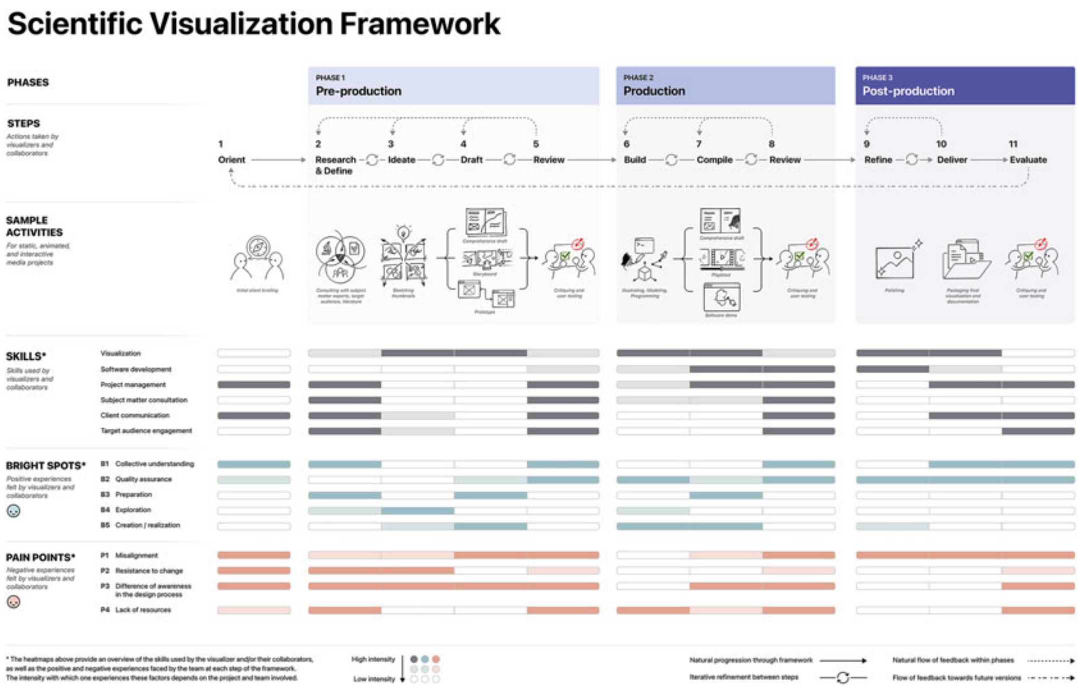


**Fig. 7.6** An overview of our proposed Scientific Visualization Framework. View a detailed version of this graphic and companion resources at sciencecomm.ca

involves refining the final product, delivering it to the client, and evaluating whether the final product has met project requirements. In the following section, we will explore each of these phases in-depth and the steps involved in achieving a successful visualization project. Figure 7.6 provides an overview of the framework's phases and specific steps. It is important to note that the number of steps within each phase is not indicative of the complexity or time invested in each phase.

A key characteristic of the framework is its highly iterative nature, allowing for repetition of the entire process or specific parts of it. This allows for continuous improvement and refinement of the product as feedback from each cycle can be used to make changes and refinements in subsequent versions of the design. The framework, from left to right, can be thought of as a cycle of continuous refinement (through a funnel) with each iteration building upon the previous one until the desired outcome is achieved. The extent to which the framework is repeated depends on budgetary constraints, the specific goals, and scope of the project. A comprehensive account of each step and phase of the framework is provided in the following.

#### 7.3.1.1 Phases and Steps

##### 7.3.1.1.1 Outset of the project

**Step 1: Orient** Gaining a shared understanding of the project requirements at the outset is critical for the success of the project. This involves engaging with all stakeholders and collaborators to ensure that everyone has a clear understanding of the project's objectives, scope, and timeline. This will serve to establish a shared vision for the project and also minimize the risk of misunderstanding and conflict later in the project.

##### 7.3.1.1.2 Phase 1: Pre-production

The pre-production phase (see Fig. 7.7) is arguably the most critical phase in the development of a visualization project, where the groundwork for the project is laid out. It involves conducting

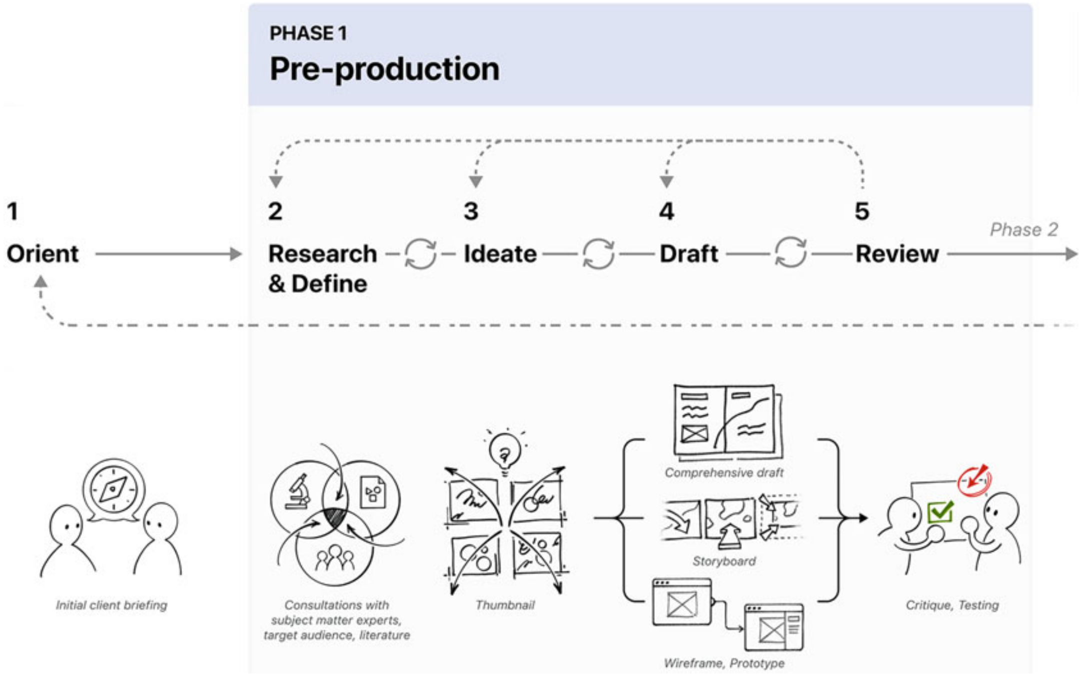


**Fig. 7.7** A close-up view of the orient step and the pre-production phase (encompassing the research and define, ideate, draft, and review steps) of the scientific visualization framework

research to gain an understanding of the content and context-of-use, defining project requirements, ideating to generate a broad range of ideas and solutions, creating drafts to elicit feedback, and conducting several rounds of review to solicit feedback from stakeholders (e.g., clients, collaborators, target audience). The ultimate goal of pre-production is to establish a clear vision for the project and ensure that the final product meets the needs of the stakeholders, especially those of the target audience.

**Step 2: Research & Define** In this step, it is important to gain a deep understanding of the project's content and context-of-use, rather than making assumptions. This involves collecting insights about the subject matter, knowledge gaps and barriers, as well as building a comprehensive understanding of the needs of the target audience within the problem space. This may include defining or redefining the project requirements based on insights gleaned from research, and crafting objectives that guide collaborators during the development of the visualization.

**Step 3: Ideate** During the ideation phase, it is important to generate as many different ideas and solutions as possible based on the problem statement formulated in either the first or second step. Keeping an open mind throughout the process and drawing inspiration from a range of sources can help generate a broad range of ideas and moderate productive discussions between visualizers, clients, and collaborators. It is also essential to involve a diverse group of collaborators in the design process to bring fresh perspectives and insights to the table.

**Step 4: Draft** In the draft step, it is important to iterate artifacts that can elicit useful feedback from collaborators and users. By doing so, one continuously improves the design concept and ensures that it meets the needs of all stakeholders.

In this step, one should carefully consider the feedback received and integrate it into future versions of the visualization.

**Step 5: Review** In the review step, it is essential to assess whether the prototype is fulfilling project requirements (defined earlier in the project) by soliciting meaningful feedback from collaborators, reviewers, and users. This step allows for the opportunity to iteratively refine the design concept based on feedback, and verify that the visualization effectively communicates the intended message, fulfills the needs of stakeholders, and meets design standards (e.g., accessibility, branding, etc.).

#### 7.3.1.1.3 Phase 2: Production

The production phase (see Fig. 7.8) is where the "actual work" is done to create the final visualization. In this phase, the team uses a variety of software and draws from reliable data sources to build individual assets and components that make up the final visualization. They may also take this time to refine approaches to the visual treatment of subject matter. The assets are then combined and integrated into a preview of the final product,

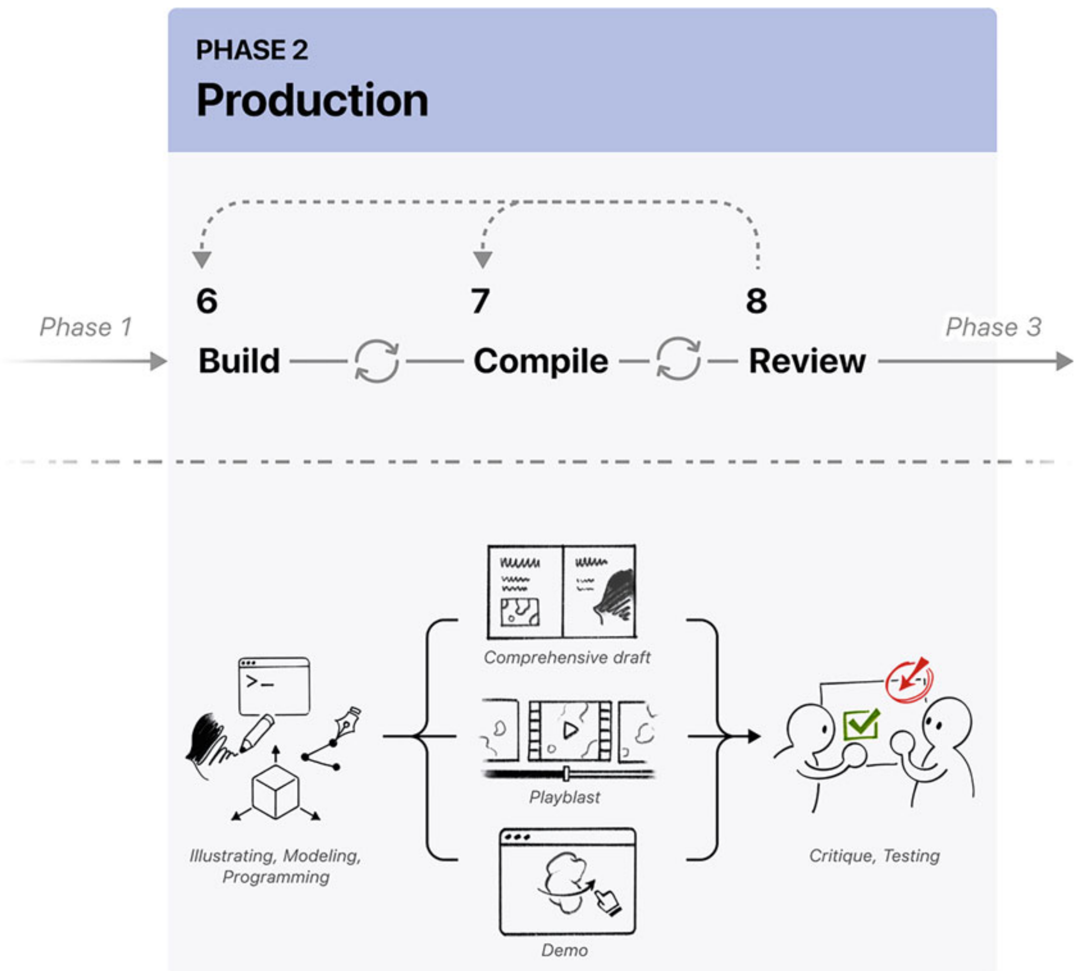


**Fig. 7.8** A close-up view of the production phase (encompassing the build, compile, and review steps) of the scientific visualization framework

which is used to solicit feedback and approval from stakeholders.

**Step 6: Build** After pre-production, the team moves on to building individual assets of the visualization. The team focuses on creating data-driven and scientifically-informed assets that will be integrated into the final visualization (in many cases, where scientific data is lacking, a discussion about the visual treatment of more speculative features would occur in pre-production). We should note the specific activities in this step vary depending on media type.

**Step 7: Compile** During this step, the team assembles assets created in the previous phase to produce a preview—a work-in-progress—of the final visualization.

**Step 8: Review** In the final step of production, the team assesses whether their work-in-progress is fulfilling project requirements (established earlier in the project) by soliciting meaningful feedback from stakeholders. This is an opportunity to use the feedback to iteratively refine the visualization; at this point, the visualization should be close to completion. It is worth noting that although it is optional to involve the target audience in this step, doing so allows practitioners to assess whether their work fulfills the communication goals identified during earlier stages of the project.

#### 7.3.1.1.4 Phase 3: Post-production

Post-production is the final phase of the visualization process (see Fig. 7.9). It involves refining the final product, delivering it to the client, and evaluating whether it has successfully met its project requirements.

**Step 9: Refine** During the refine step, the team adds the finishing touches to the final visualization that tie together all assets generated during production. The team will undergo a final round

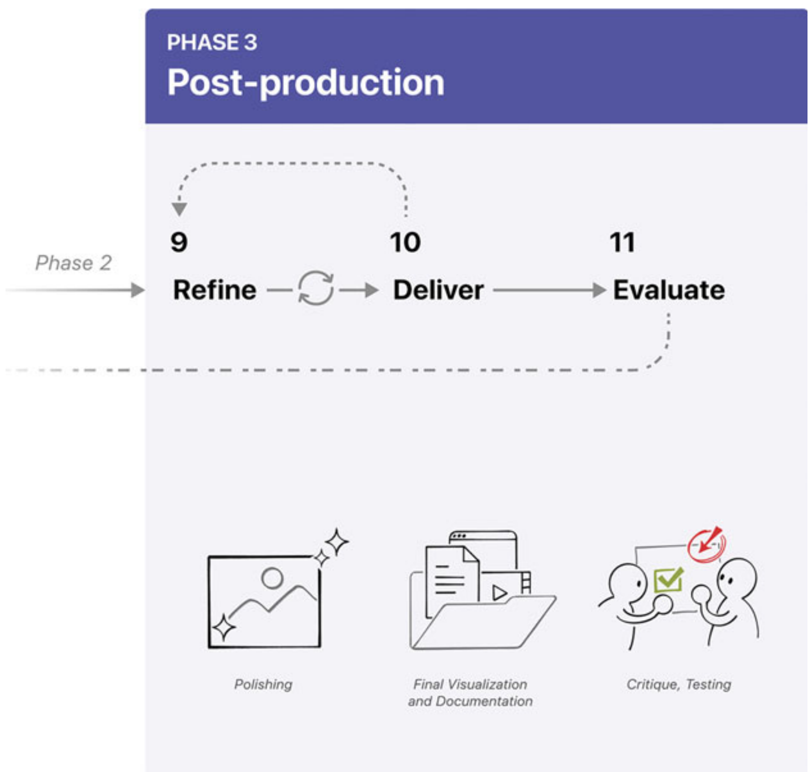


**Fig. 7.9** A close-up view of the post-production phase (encompassing the refine, deliver, and evaluate steps) of the scientific visualization framework

of review to verify all aspects of the visualization (e.g., ensure the science has been accurately conveyed; ensure the visualization meets existing design standards in the problem space; etc.).

**Step 10: Deliver** Once the final product has been thoroughly polished, reviewed, and approved, it can be delivered to the client. In this step, the team packages the final visualization files and project documentation, adhering to the client's specified dissemination requirements.

**Step 11: Evaluate** In this final step, it is important to assess (informally or formally)—with the intended audience of the visualization—whether the final product has actually fulfilled the project requirements defined at the start of the project. This is an opportunity to reflect on the project as a whole and identify areas for improvement in future projects.

#### 7.3.1.2 Skills

Drawing on the case studies above and our collective experiences, we distilled a set of skills that are often required for crafting scientific visualizations of varying media types. These capabilities are illustrated in the heatmap diagram presented in Fig. 7.6. These key skills can be grouped into six categories: visualization (e.g., ability to create visual sketches, drafts, final assets, etc.), software development, project management, subject matter consultation (e.g., ability to provide scientific expertise), client communication, and target audience engagement (e.g., ability to conduct focus groups, usability tests with users, etc.). It is important to note this heatmap provides a generalized view of the skills used by the visualizer and their collaborators, and the intensity with which one experiences these factors depends entirely on the project and team involved.

#### 7.3.1.3 Activities & Outputs

To effectively execute the framework, the practitioner actively performs activities and creates outputs that contribute to the design of the final visualization. Table 7.2 shows a breakdown of the types of activities and outputs that occur at each step of our proposed framework.

#### 7.3.1.4 Bright Spots & Pain Points

The framework includes a detailed breakdown of "bright spots" and "pain points" that reflect—in the authors' collective experiences—the benefits, challenges, and limitations of employing this framework. In this section, we use bright spots as a term to describe positive experiences felt by visualizers and their collaborators during the visualization process, while pain points refer to negative experiences.

##### 7.3.1.4.1 Bright Spots

In the context of the proposed framework, "bright spots"—positive experiences felt by visualizers and their collaborators—can be seen as "hot spots" where things have a greater potential for working well, and the conditions are favorable for achieving desired results (assuming the team takes advantage of these opportunities). We group bright spots into five broad categories listed below from B1 to B5; these are further broken down and mapped against each step of the framework in Table 7.3.

**B1: Collective Understanding** This refers to the shared understanding among team members about the project's goals, expectations, and requirements. When there is collective understanding, everyone is on the same page (i.e., shared definition of success can help to ensure that the project meets all requirements and leads to satisfaction from all stakeholders), which can lead to better collaboration, communication, and decision-making.

**B2: Quality Assurance** This bright spot involves identifying and addressing issues early in the design process (while the design is still easily editable), as well as reviewing and verifying the accuracy and effectiveness of the final product at checkpoints throughout the process (to ensure the delivery of a high-quality visualization).

**Table 7.2** Detailed breakdown of the activities and example outputs at each step of the framework

| Steps of the Framework | Activities | Example outputs |
|---|---|---|
| Step 1: Orient | It is important to begin with a clear understanding of the visualization objectives, target audience, medium, and venue. This can be achieved through a project kick-off meeting where the project requirements are discussed and realistic expectations are established. It is important to ensure that the project fits within existing knowledge, literature, and reference materials, while also aligning with the needs of the users. Additionally, it is crucial to have the necessary resources in place, including financial support, time, and team members to deliver a successful solution. At this time, it is also important to identify a list of contributors who will be active collaborators and reviewers throughout the project. Finally, a project schedule or plan should be created and shared with the team to ensure everyone is on the same page and working toward the same goals. Following these steps ensures a greater likelihood of success at the outset. | Project brief. |
| Phase 1: Pre-production | | |
| Step 2: Research & Define | It is important to understand the needs, behaviors, and beliefs of the users and stakeholders. This can be accomplished through a combination of primary and secondary research. Primary research can include user research where the audience is observed and engaged through interviews, surveys, and field research. Secondary research can include collecting existing research documents from the client, conducting a literature review, competitor analysis, and market research.<br>After collecting and synthesizing the research findings, the project can be defined more specifically. This involves confirming or redefining the visualization objectives, target audience, medium, and venue that were established in Step 1: Orient. It is also important to define the problem statement and identify the content, design, and functional requirements for the project. By following these steps, the project can be tailored to meet the needs of the users and stakeholders and result in a successful visualization. | Research notes, key message/story statement, initial treatment ideas.<br>● Static imagery: Content outline.<br>● Animation: Script.<br>● Interactive: Scope document, needs assessment, user personas, context scenarios. |
| Step 3: Ideate | It is important to generate a variety of potential solutions when one is trying to solve the visualization problem identified in Step 2: Research and Define. A variety of ideas can be generated through brainstorming sessions, mind maps, rough sketches, thumbnails, etc. These methods help with exploring different concepts and refining existing ideas.<br>It is also helpful to collect inspiration from others when working on visual development. This involves gathering examples of successful visualizations, analyzing their effectiveness, and | Thumbnails, concept art, style frames.<br>● Animation: Rough storyboards, color keys.<br>● Interactive: Co-creation, prioritization matrices, UX storyboards. |

(continued)

**Table 7.2** (continued)

| Steps of the Framework | Activities | Example outputs |
|---|---|---|
| | using this new found knowledge and perspective to inform the development and refinement of new concepts. | |
| Step 4: Draft | After generating a variety of ideas, it is important to evaluate them and determine which approaches are likely to be the most effective. From there, drafts can be prepared with increasing levels of fidelity to further refine and develop the ideas. It is important to ensure that these prototypes contain the information necessary to solicit meaningful feedback, reactions, and responses. | ● Static imagery: Comprehensive draft.<br>● Animation: Refined storyboards, animatic.<br>● Interactive: Design document, wireframes, interactive prototype, content inventory. |
| Step 5: Review | To ensure that the proposed draft meets the visualization goals, it is important to assess its quality informally on a small scale*. This can be accomplished by reviewing the draft and identifying areas that require further refinement and improvement. These reviews can be conducted as a critique session with the project team (as a group or individually) to solicit feedback and identify areas that require further attention. Depending on the project, pilot tests with users can also be conducted to gain insights into how the visualization will be used and its overall effectiveness.<br>Additionally, revisiting the project requirements is essential at this point to determine whether the objectives, target audience, medium, and venue need to be revised based on newly acquired insight. It is also important to conduct a preliminary check for standards compliance, such as venue/outlet specifications, accessibility, and federal/provincial requirements. Based on the insights gained, the prototype can be revised to ensure that it meets the desired objectives and effectively communicates the intended message to the target audience.<br>*Note: In some scenarios, a formal evaluation may be required at this stage.* | Feedback documents, comments. |
| Phase 2: Production | | |
| Step 6: Build | To build effective and accurate assets, it is important to first collect all the necessary data and reference materials. Once all the required materials are collected, specialized software can be used to visualize the data in a meaningful way. | Asset files<br>● Static imagery: 2D illustrations.<br>● Animation: 3D models.<br>● Interactive: Interactive elements in different states (e.g., buttons). |
| Step 7: Compile | At this step, it is important to compile all the assets created during the previous steps into a cohesive whole. This involves collecting all the visual and written content, and combining it into a version that effectively communicates the intended message to the target audience. This version can then be used to solicit meaningful feedback, reactions, and responses from stakeholders and users, and ultimately identify areas for improvement. | ● Static imagery: Refined comprehensive layout.<br>● Animation: Playblast (a low-fidelity sample of the animation), test render (high-fidelity sample of the animation).<br>● Interactive: Software demonstration. |
| Step 8: Review | Same as *Step 5—Review.* | Feedback documents, comments. |

(continued)

**Table 7.2** (continued)

| Steps of the Framework | Activities | Example outputs |
|---|---|---|
| Phase 3: Post-production | | |
| Step 9: Refine | After collecting feedback from stakeholders and making any necessary final edits, it is important to prepare the final visualization for dissemination. This involves cleaning up files, verifying that all dissemination or submission requirements have been met, and ensuring that the final visualization complies with all relevant standards. It is also recommended that the visualization be reviewed by a subject matter expert to verify the accuracy of the content. | Final visualization. |
| Step 10: Deliver | Once the final visualization has been created and meets all necessary requirements, it is time to export the file(s) for the client in a format that is suitable for dissemination. Additionally, it is crucial to properly save any relevant project documentation and working files; this can aid in future updates or modifications if needed. Lastly, it is important to properly credit and acknowledge any contributors or sources if applicable. | Final visualization files, project documentation. |
| Step 11: Evaluate | In this final step, it is important to assess the quality and effectiveness of the visualization in achieving the goals set at the start of the project. This can be achieved through formal evaluations with evaluators and users. Although less desirable, an informal evaluation, in the form of a debrief within the team or by oneself can also be helpful in identifying areas for improvement or future development. Finally, it is important to assess the impact of the visualization through analytics, which can provide data on how many people viewed or interacted with the asset, and how they engaged with the content. By following these steps, the quality and effectiveness of the visualization can be evaluated, and areas for improvement for future development can be identified. | Usability report, feedback documents, comments. |

Example outputs may differ depending on the media type of the visualization

**B3: Preparation** Preparation refers to the various points in the design process where the team generates materials and documents that serve as a roadmap for the visualization process (particularly during the pre-production and production stages). These materials may take the form of detailed project plans, timelines, budgets, and other relevant documents that guide the team in the production process. Additionally, preparation involves creating key design artifacts and other documents that are important for soliciting meaningful feedback from collaborators and other stakeholders. These materials provide guidance and clarity for the entire team, streamlining the production process and help to ensure that the project is completed on time, within budget, and to the satisfaction of all stakeholders.

**B4: Exploration** This bright spot refers to points in the design process where the team investigates a variety of possible design solutions, with the goal of uncovering unexpected, unique, and

**Table 7.3** Detailed breakdown of the bright spots and pain points experienced by visualizers and/or collaborators at each step of the framework

| Steps of framework | Bright spots | Pain points |
|---|---|---|
| Step 1: Orient | (B1, B2) Clarify project expectations: Clients have an opportunity to provide context while visualizers can ask probing questions to further clarify their request. As a result, a shared definition of success becomes more evident for the team.<br>(B1) Build new understanding:<br>By sharing their own perspectives, clients and visualizers may come to a new understanding of the project requirements.<br>(B1) Achieve alignment: Clients and visualizers communicate their expectations, responsibilities, and schedule. | (P1, P3) Time-intensive onboarding: Visualization team may need to invest time to onboard/educate clients and other teammates who are unfamiliar with the design process.<br>(P3, P4) Cutting corners: Negotiate budget, and cutting important steps of the process to accommodate limited resources.<br>(P2, P3) Resistance to changing design approach: Client is set on a certain visualization request and is resistant to exploring different design approaches suggested by the team. On the other hand, the visualization team is set on a certain design approach and is resistant to accommodating client requests.<br>(P1, P3) Lack of shared vocabulary: Client has difficulty in communicating the challenge or problem space. On the other hand, the visualization team is unable to properly interpret the client's request. |
| Phase 1: Pre-production | | |
| Step 2: Research and Define | (B1) Build deeper understanding: Visualizers acquire a nuanced understanding of the problem, the audience, and the context-of-use through primary and secondary research, exploring various dimensions of the issue at hand.<br>(B1) Achieve alignment:<br>The team becomes more strongly aligned by defining a common problem statement.<br>(B3) Prepare for pre-visualization phase: Generate documents that will serve as a roadmap for the rest of the pre-production stage. | (P2, P3) Resistance to redefining the problem: Client is resistant in changing their preconceived notion of the problem space, and/or target audience. Alternatively, the visualization team may be unwilling to challenge their own assumptions.<br>(P4) Limited resources that affect project scope: Lack of resources to perform research and analysis (expertise, finance, time, access to users, etc.).<br>(P3) Lack of awareness and/or appreciation: Cutting important steps because client and team are not aware and/or do not appreciate the importance and purpose of each step of the design process.<br>(P1) Lack of communication and engagement: A lack of communication and collaboration leads to an inaccurate definition of the problem space and project objectives. This may not be readily apparent, but will cause issues down the line. |
| Step 3: Ideate | (B4) Open-minded exploration: Uncover unexpected, unique, and potentially effective design solutions by exploring many possible options. | (P1, P2, P3) Jumping to conclusions: Difficulty brainstorming the potential design approaches for the project due to early judgment, devil's advocate, unclear goals, inexperienced facilitations, etc.<br>(P2, P3) Lack of awareness of design possibilities: Client, stakeholders and team do not understand and/or are not aware of the universe of multimedia possibilities or the design approaches that can be employed.<br>(P2, P3) Resistance to partnership and collaboration: Client is set on a certain |

(continued)

**Table 7.3** (continued)

| Steps of framework | Bright spots | Pain points |
|---|---|---|
| | | visualization idea and treats the team as a vendor (production studio) as opposed to a partner. |
| Step 4: Draft | (B2, B3) Prepare material for soliciting feedback: Create material used to solicit meaningful feedback from collaborators.<br>(B3) Prepare for visualization phase: Create materials used to guide production for internal team members. | (P1, P3) Client does not understand the draft and/or draft makes the wrong impression: The fidelity of the draft affects judgment. For example, a client may mistake storyboards or animatics for final products rather than artifacts intended for feedback and critique. They may understand the purpose, but focus on the wrong things. On the other hand, the visualization team creates artifacts that are not appropriate for review, which can make it difficult for people to provide meaningful feedback. The draft may be too rough to be comprehensible to reviewers, or too polished, making reviewers feel like their input is no longer needed or valid. |
| Step 5: Review | (B2) Identify issues: Catch and address issues while the design is still easily editable.<br>(B2) Prevent issues: Ensure the emerging plan is on the right track, and the project is meeting its requirements.<br>(B1, B2) Solicit meaningful feedback: Use the materials created to solicit valuable feedback.<br>(B1) Achieve alignment: An opportunity for collaborators, clients, and users to communicate expectations. | (P4) Limited resources that affect project scope: Lack of resources to carry out review (e.g. Limited or no access to users, other stakeholders, expertise, finance, time, etc.).<br>(P3) Missed opportunities: Project team does not review the draft seriously or thoroughly enough, missing an opportunity to address issues when the project is still easily editable.<br>(P1, P3) Resistance to changing design approach: The client and designers do not meet eye to eye and are resistant to change. |
| Phase 2: Production | | |
| Step 6: Build | (B2, B5) Create scientifically-informed assets: Create visual interpretations informed by available scientific evidence.<br>(B4) Guided exploration: Explore lighting/texturing, etc. and other stylistic decisions that could not be made in the pre-visualization stages. | (P4) Technical issues, expected and unexpected: Technical issues due to a variety of reasons (lack of expertise, unexpected issues, etc.). |
| Step 7: Compile | (B5) Realize end product: String assets together into a cohesive preview of the final product.<br>(B2, B3) Prepare material for soliciting feedback: Create material used to solicit meaningful feedback from collaborators.<br>(B3) Prepare for post-visualization phase: Create materials used to guide production for internal team members. | (P1, P3) Client does not understand the preview and/or preview makes the wrong impression: The fidelity of the preview affects judgment. For example, a client may mistake a play blast of an animation for final products rather than artifacts intended for feedback and critique. They may understand the purpose, but focus on the wrong things. On the other hand, the visualization team creates artifacts that are not appropriate for review, which can make it difficult for people to provide meaningful feedback. The preview may be too rough and illegible or too polished, making people feel like their input is no longer needed or valid. |
| Step 8: Review | (B2, B3) Prepare material for soliciting feedback: Create material used to solicit meaningful feedback from collaborators.<br>(B1,B2) Solicit meaningful feedback: Use the | (P4) Limited resources that affect project scope: Lack of resources to carry out review (e.g. Limited or no access to users, other stakeholders, expertise, finance, time, etc.). |

(continued)

**Table 7.3** (continued)

| Steps of framework | Bright spots | Pain points |
|---|---|---|
| | materials created to solicit valuable feedback.<br>(B1) Achieve alignment: An opportunity for collaborators, clients, users to communicate expectations with one another. | (P3) Missed opportunities: Project team does not review the preview seriously or thoroughly enough, missing an opportunity to address issues when the project is still easily editable.<br>(P1, P3) Resistance to changing design approach: The client and designers do not meet eye to eye and are resistant to change. |
| Phase 3: Post-production | | |
| Step 9: Refine | (B5) Realize end product: Add final touches to the visualization.<br>(B2) Prevent issues: Final opportunity to ensure the project is on the right track and meeting its requirements. | (P1) Last-minute changes: During this period of low editability, major feedback surfaces lead to frustration, a change in direction, and an increase in deadline and resource-related pressures. |
| Step 10: Deliver | (B2, B3) Prepare material for soliciting feedback: Create material used to solicit meaningful feedback from collaborators. | (P1) Miscommunication: There is difficulty wrapping up a project because project requirements have not been clearly communicated.<br>(P1) Last-minute changes: During this period of low editability, major feedback surfaces leading to frustration, a change in direction, and an increase in deadline and resource-related pressures. |
| Step 11: Evaluate | (B2, B3) Prepare material for soliciting feedback: Create material used to solicit meaningful feedback from collaborators. | (P4) Limited resources that affect project scope: Lack of available resources to conduct evaluation (e.g. limited access to users, expertise, budget, time, etc.).<br>(P3) Missed opportunities: Team does not see value or reason in evaluating the visualization. |

Legends for bright spots: B1: Collective understanding; B2: Quality assurance; B3: Preparation; B4: Exploration; B5: Creation/realization. Legends for pain points: P1: Misalignment; P2: Resistance to change; P3: Difference of awareness in the design process; P4: Lack of resources

effective approaches to solve the challenge. By investing time in the exploration of options, ideas, and approaches, the team can increase the likelihood of creating a final visualization that is more effective and impactful.

**B5: Creation/Realization** This occurs when the team utilizes all of the insights and materials generated during the previous stages to bring the visualization to life (i.e., actual creation or realization of the project deliverables). This stage involves the use of scientific information to create an accurate visual representation of the subject matter, bringing together various assets into a cohesive preview of the final product, adding final touches to the visualization, and delivering a compelling and impactful visualization that meets the needs and expectations of the project.

#### 7.3.1.4.2 Pain Points

In the context of the proposed framework, "pain points"—negative experiences felt by visualizers and their collaborators—are considered "high-risk zones" where unfavorable circumstances are more likely to occur and cause a situation to deteriorate rapidly (assuming the team does not take the necessary steps to mitigate the potential risks and/or address the issues in a timely manner). The framework details four broad categories of pain points listed below from P1 to P4; these are further broken down and mapped out against each step of the framework in Table 7.3.

**P1: Misalignment** Misalignment refers to a pain point where different stakeholders or teams involved in the design process have conflicting goals, priorities, or approaches. This may arise due to a variety of reasons, including time-intensive onboarding, lack of shared vocabulary, miscommunication and engagement issues. Ultimately, this misalignment can result in confusion, delays, or suboptimal outcomes.

**P2: Resistance to Change** This pain point refers to instances in the design process where the client, visualization team, or other stakeholders are hesitant or unwilling to explore/adopt new ideas, designs, workflows, or technologies. This resistance can arise from a variety of factors, such as a lack of familiarity or trust in the new approach, or concerns about the potential costs or risks associated with change. On the client side, this may manifest as a reluctance to explore different design approaches suggested by the team or a resistance to redefining the problem space or target audience. On the other hand, the visualization team may be fixed on a certain design approach and resistant to accommodating client requests. At the core of this pain point is a resistance to partnership and collaboration and lack of trust between the team.

**P3: Difference of Awareness in the Design Process** This pain point arises when different stakeholders or teams involved in the project have differing levels of knowledge, understanding and/or appreciation of the design process and/or the impact of design strategy upon communication. For instance, many tend to see visual style purely as a feature that drives esthetics and engagement, when it can also have an impact on communication objectives. These issues can include time-intensive onboarding, resistance to changing design approaches, lack of shared vocabulary, resistance to redefining the problem, jumping to conclusions or cutting corners (by skipping critical steps in the process) and missed opportunities to thoroughly review drafts and previews. As a result, the probability of producing an unsatisfactory or ineffective final visualization increases when the team does not recognize the importance of each step in the design process.

**P4: Lack of Resources** This pain point refers to instances where the team does not have sufficient time, budget, personnel and/or expertise to execute the design process effectively. For example, this might occur when the design team advocates for one solution over another because they lack the requisite skills or resources to implement the design solution best suited to the communication goal. Limited resources can significantly impact the project scope, leading to cutting corners, and the removal of important steps from the design process to accommodate for the lack of resources.

## 7.4 Potential Applications of the Framework

### 7.4.1 Planning and Onboarding

Through developing this framework for scientific visualization, we've identified the key steps in the design process practiced by visualization teams as well as the necessary skills, activities, outputs, bright spots, and pain points associated with each step. Practitioners, particularly novices-in-training, can take advantage of these learnings when planning for upcoming projects with their clients. By using this framework, visualizers introduce clients to the complexity and nuances of visualization as well as a shared vocabulary for communicating their ideas effectively. By understanding the role that different activities and outputs play in contributing to the final visualization design, the team will be more inclined to invest time and resources into them. Ultimately, we envision that visualizers, clients, and their peripheral collaborators can build a more robust workflow that helps them anticipate and prepare for potential obstacles during the course of a visualization project. Simply convincing clients that they are investing in a creative process, rather than a singular output like a graphic or an animation, can set the stage for collaboration and successful navigation of the many steps in this creative process.

### 7.4.2 Workflow Improvement Tools

We can also use the framework to pinpoint areas in the visualization process that can be improved by the development of new workflow tools and resources. For instance, it can be challenging to explore potential visualization approaches with clients during pre-production, especially for those new to visualization. To address this challenge, two of the authors (McGill and Saharan) designed a Multimedia Design Atlas (MDA) (https://multimediadesignatlas.notion.site/) that helps designers and clients learn and discuss the universe of multimedia categories and design possibilities when creating educational materials. By introducing the different media formats and their features, such as their pedagogical affordances and technical specifications, clients are made aware of the range of design options available to them and can make more informed decisions when selecting a media type for the final visualization early in the pre-production process.

## 7.5 Limitations of the Framework

While the proposed framework has been designed with good intentions, its adoption into practice may be challenging due to a variety of reasons. Below, we discuss how factors such as applicability, resource availability, framework validation, and the inherent complexity of the visualization process can impact the use of our framework in practice.

### 7.5.1 Lack of Validation

At this time, a limitation of the proposed framework is the lack of validation for its effectiveness and impact. Although the framework draws on an analysis of several conceptual frameworks as well as the author team's combined ~60 years of experiences in scientific visualization, it has not yet been validated in a real-world context. This raises questions about the framework's generalizability and applicability across the current landscape of work in scientific visualization—projects with different contexts-of-use, media types, target audiences, team compositions, and more.

A lack of validation limits opportunities for refining the framework based on feedback and insights from its potential users (i.e., collective experiences of visualizers and clients outside the author team). To address this limitation, the author team aims to evaluate the effectiveness of the framework in diverse contexts (e.g., different audiences, media types, environments, etc.), using existing or new methodologies to assess its usability and value in the real world. Moving forward, the author team hopes that validating this framework with empirical evidence can help to establish its credibility and efficacy, facilitating broader adoption by the scientific visualization community.

### 7.5.2 Challenges with Applicability

This framework is generalizable and so will need to be tailored to factors such as the project's specific subject matter, media type, team composition, expertise, organizational structure, and more. For example, potential adopters from another creative field may be deterred simply by the use of differing terminology as presented in our framework. Potential adopters may also need to modify their existing workflows and secure additional resources (e.g., budget) to implement our proposed framework. This is a time-consuming investment that is often met with resistance from stakeholders and decision-makers.

### 7.5.3 Resource Intensiveness

Another limitation of this framework is that it will require an investment of time, money, expertise, and other resources to implement effectively in any given context. Although beneficial, the steps of the framework—from *Orient* to *Evaluate*—are resource intensive. In some cases, projects may require specialized knowledge, access to content experts and/or target users, and acquisition of specific software and hardware, which could exclude potential adopters from implementing the proposed framework. Ultimately, a lack of resources could limit scalability, particularly for teams that have budgetary or time-related constraints. The implementation of this framework may also pose a challenge for individuals or teams who are not trained in the specific set of skills listed in the framework, nor have access to outside expertise ranging from subject matter to technical expertise.

### 7.5.4 Inherent Complexity of the Visualization Process

Lastly, the inherent complexity of the visualization process (and our interpretation of it) may pose a limitation to potential users of our framework. One example is the reality of collaboration and communication in an iterative design process. The proposed framework is highly iterative and collaborative, and as a result, its success is dependent on continuous and meaningful engagement between team members and stakeholders. Managing these projects can be challenging, particularly when working with a large and diverse group of individuals who have competing priorities. These challenges can lead to common project pitfalls such as misaligned expectations for the final visualization, which can cause frustration and hinder progress.

As presented in this chapter, the framework may be challenging for potential audiences to understand and ultimately implement in their work. Even with sufficient documentation (as presented in this chapter), scientific visualizers may feel discouraged to adopt this framework and practice it on a day-to-day basis. To address this limitation, the author team is in the process of developing a more practical and accessible toolkit version of the chapter, found at sciencecomm.ca. This companion guide will provide scaffolding for practitioners looking to use the framework, giving them the ability to modify and adapt the framework to meet their specific project requirements so they can use it with their clients and within their own teams.

## 7.6 Conclusions

In this chapter, we present a comprehensive framework for designing, producing, and evaluating scientific visualizations. Drawing on case studies and conceptual frameworks, we illustrate how our proposed framework can support the development of static, animated, and interactive media types, from initial conception to final evaluation. Throughout this process, we emphasize the importance of iterative feedback cycles and their role in refining and improving visualizations. We establish connections between the steps outlined in this framework to the activities, outputs, and individuals that impact design decisions and ultimately the flow of the overall design process. Lastly, we assess each step of the framework for its bright spots and pain points to give readers a clear understanding of the potential benefits and challenges of using this approach.

Our ultimate goal in proposing this framework is to support scientific visualization practitioners in building a design process that meets their objectives and facilitating productive conversations with clients and collaborators about the importance of a robust design process. This in part led us to develop a practical toolkit (located at https://sciencecomm.ca) that provides scaffolding for practitioners looking to implement our framework. However, further research is needed to establish the extent to which this framework is valid and fulfills this goal. Future directions for our research include validating the visualization framework by applying it to real-world projects within the visualization design space and measuring its relative efficacy when compared with current practices and existing design frameworks.

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