What Makes Tweetorials Tick: How Experts Communicate Complex Topics on Twitter

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People are increasingly getting information and news from social media. On Twitter we are seeing the emergence of "tweetorials" – long, explanatory Twitter threads written by experts. In this work we study tweetorials as a form of science writing. While scientists have begun to champion the importance of Twitter as a science communication medium, few have studied how people are successfully using this medium to communicate complex and nuanced ideas. To understand how tweetorials work, we curated a collection of 46 clear and engaging tweetorials from multiple domains. We analyzed these tweetorials for the writing techniques that they employ, and found that while tweetorials use many traditional science writing techniques, they also use more subjective language, actively build credibility, and incorporate media in unique ways. In addition, we report on a workshop we ran to aid science PhD students in writing tweetorials, and find that while providing common tweetorial techniques improves their writing, the students still struggle to balance their scientific sensibilities with the informal tone associated with tweetorials. We discuss the implications of using informal and subjective language in science communication, as well as how technology can support scientists in writing tweetorials.

CCS Concepts: • **Human-centered computing → Collaborative and social computing**; • **Applied computing → Education**.

Additional Key Words and Phrases: Science communication, science writing, social media, Twitter, tweetorials

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1 INTRODUCTION

More and more people are learning about the world not from newspapers or magazines, but from social media [49]. This information can come directly from experts, who have found social media to be a straightforward and low-barrier way to communicate their expertise to the public [52]. In particular, Twitter has become a popular platform for experts of all kinds. While academic communities on Twitter have been studied extensively [19, 35, 46], with a particular focus on how

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Twitter is used during academic conferences [39, 47], less attention has been paid to how scientists are using Twitter to communicate to a wider audience, despite evidence that scientists can garner a large and diverse social media following [13].

An emerging format for explaining complex concepts on Twitter is the tweetorial. A tweetorial is a series of tweets that display sequentially on the Twitter platform and explain a technical concept [11, 12]. Tweetorials explain topics of all kinds, from the medical domain (e.g. why your fingertips wrinkle in the bath) to the computer science domain (e.g. how hash functions work).

Despite the popularity some tweetorials and their authors have garnered, there are few resources that support scientists looking to partake in this kind of science writing. In this paper, we use a science communication lens to identify **writing strategies that clear and engaging tweetorials employ**, in order to encourage and empower more scientists to write tweetorials about their own work and areas of expertise. Additionally we describe **the difficulties that science PhD students encounter in employing these strategies**, and outline challenges and opportunities for helping them write tweetorials.

We curate and release an annotated set of 46 tweetorials that explain concepts from a variety of domains for a general audience. We report on how the tweetorial relates to more traditional science writing formats like news articles, opinion pieces, and feature stories by showing how they conform to a lede-body-conclusion structure, and where their rhetorical techniques differ from common advice. In addition, we present an initial investigation into how science PhD students approach writing tweetorials by reporting on a workshop we held. This workshop brought science PhD students and professional science writers together to help the students write tweetorials about their area of research.

Our contributions are:

- an annotated set of 46 tweetorials from a variety of domains[1];
- an analysis of writing techniques used in these tweetorials and how they relate to traditional science writing advice; and
- a series of findings about what science PhD students struggle with when writing tweetorials about their own work.

2 RELATED WORK

2.1 Informal Online Learning and Social Media

CSCW and related venues have a long history of studying informal, online learning communities [22, 56, 60], and attention is turning to social media as it becomes a platform for knowledge discovery and sharing. The Reddit 'Ask' communities have been studied as self-moderated 'learning in the wild' groups that can build trust in the academic process [25, 27]. Online videos have become a major venue for informal science communication: Welbourne and Grant found that user-generated science videos are more popular than professionally generated ones [61]; Sugimoto and Thelwall focused on TED videos and found that science and technology videos have more impact than art and design ones [54].

Twitter has been shown to be a major spreader of scientific resources [64], and academic communities on Twitter have been studied extensively, with researchers reporting that Twitter is useful in facilitating knowledge exchange and building academic support networks [19, 35, 46]. There is a particular focus on how Twitter is used as a back-channel and informational resource during academic conferences [39, 47].

Less research has been done on how social media is used as a venue for more public science communication, despite evidence that experts can garner a large and diverse following [13], and advice

[1] https://github.com/kgero/what-makes-tweetorials-tick/

from high-profile scientists advocating for more scientists to use social media as a communication platform [13, 52]. Research has found that scientific Reddit communities such as r/science and r/askscience have linguistic barriers of entry, where successful posters use more formal language than transient posters [3]. Others have shown that creating engaging content for social media is difficult due to a lack of clear guidelines on what improves engagement and differences in audience preferences across platforms [2]. Huang and Grant found that science videos on YouTube are more popular if they contain storytelling components [30]. But there is still much to learn about how scientific outreach on social media works.

Over the past two decades in science writing research, more and more evidence has been mounted against the 'deficit model' of education [51], which assumes general audiences simply need to be shown more facts to become more educated. In contrast, research finds that a more participatory approach, in which scientists listen to the public's concerns and cater their message in response, is more likely to change minds. Nisbet and Schefuele [45] summarize empirical findings that rebut the deficit model, and report on how science writing is most effective when people can be in dialogue with the scientists, as well as policy makers and other stakeholders. Social media is poised to be a participatory tool scientists can use for effective communication, though many call for more work to be done to properly understand its role and how to use it most effectively [29, 43, 63]. This leaves a gap in the literature to study effective social media-based science writing. Our work explores the emergence of common practices, and the difficulties scientists have in adapting to them.

2.2 Traditional Science Writing Best Practices

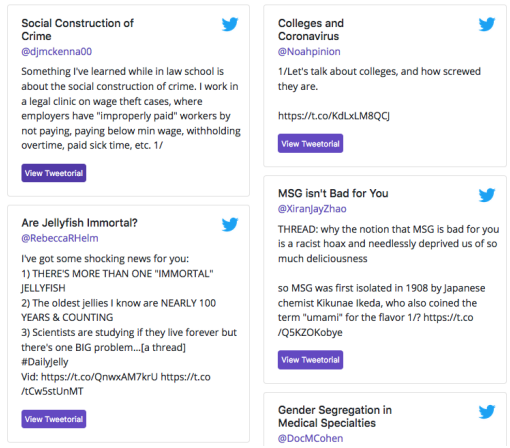
Science writing education has a rich history of sharing best practices derived from decades of experience writing for the public, long before the emergence of social media. These educational resources typically prepare scientists for writing newspaper articles, opinion pieces, or other longform articles distributed outside their academic field. Part of our work is exploring how these practices are being adapted to social media.

Although each educational resource has a unique perspective, there are themes that are shared across all. We draw on a variety of sources, from science writing communities and editors [15, 44, 53, 65] to books on craft [8, 32], and summarize the major themes below.

- *Writing has an implicit structure.* The beginning of a piece, called the lede, must entice the reader to continue reading, while the conclusion should return to anything set up in the lede.
- *The lede should hook the reader.* The lede is the opening sentence or paragraph of an article, and needs to convince the reader to continue reading. Ledes should hook the reader with something attention-grabbing: clear, concise, but ultimately unfinished, such that the reader will want to learn more.
- *Specific stories are a driving force.* Writing propelled by characters and narratives is much more compelling than an explanation of abstract ideas, generalizations, or statistics. Specific events and hurdles are more engaging than stating facts.
- *There are many tricks for explaining.* Explaining technical details is difficult, and is often where writers lose their readers. Experts must be especially careful to avoid jargon and other words that confuse or discourage readers. Explanatory strategies include analogy and metaphor, non-examples, and small stories.
- *The ending is not a summary.* Conclusions should return to the questions posed early on in the article–the suspense that first drew the reader into the article–and place the article within a larger context.

We studied tweetorials with the understanding that although they are an emerging social media format, they are likely to draw on the same science writing techniques distilled from more traditional

(a) First three tweets of a tweetorial about dung beetle navigation by @GeneticJen. Source: https://twitter.com/GeneticJen/status/897153589193441281.



(b) Sample of our collected tweetorials in a web-browsable format. Each card shows the first tweet in the tweetorial, and the full tweetorial can be viewed by clicking on the card. Link to be shared after anonymous review.

Fig. 1. Examples of tweetorials.

mediums. But we also found that these educational resources describe the qualities of excellent science writing without always demonstrating what techniques a writer might use to achieve these qualities. For example, while all resources explain the qualities of a good lede and occasionally give examples, few report typical strategies used to create a good lede.

In our work, we sought to identify how tweetorials diverge from this conventional wisdom, and why. But we also sought to identify the strategies used in tweetorials, such that scientists can use these strategies when writing their own tweetorials.

2.3 Tweetorial Definitions and Evolution

A Twitter thread is a chronological list of tweets where each tweet is a reply to the one before, and the author of all the tweets is the same. In late 2017, Twitter made threads easier to view; at the same time, they increased the character limit for each tweet from 140 to 280 [48]. Both Breu and Berstein trace the origin of the tweetorial in the medical community to late 2017, just as Twitter made these changes [5, 12]. Breu suggests that tweetorials are an offspring of tweetstorms, which are a series of tweets from a single author posted in quick succession.

The medical community seems to be an early adopter of Twitter as a forum for continuing education, as they popularized the hashtag #medtweetorials, wrote papers about it [11, 12], and started a website[2] to collect these tweetorials and tag them by medical specialty. These tweetorials tend to be aimed at other medical professionals and often contain a lot of jargon.

However, others are writing tweetorials as well. If we use Breu's definition of tweetorials as a "collection of threaded tweets aimed at teaching users who engage with them" [11], then we can identify many tweetorials being posted across many different disciplines, and seemingly with a wider audience in mind. An early author is @GeneticJen who posted popular tweetorials in 2017;

[2] https://medtweetorials.com

one tweetorial of hers on the topic of dung beetle navigation has received over 9,800 likes[3]. Since 2017, the popularity of this form has only increased [5]. See Figure 1 for example tweetorials.

3 STUDY 1: ANALYSIS OF TWEETORIALS

In order to understand how people are currently using tweetorials to communicate complex material to a general audience, we curated a set of tweetorials from a wide range of domains. We drew from both scientific domains as well as from the social sciences and humanities, as we believe that the explanatory strategies used in all fields are relevant for science communication. We then analysed our set of tweetorials for their structure and use of rhetorical strategies. In particular, we posed the following research question:

> *RQ1: What writing strategies do tweetorials employ and how do they differ from traditional science writing recommendations?*

3.1 Data Collection

3.1.1 Criteria for selecting tweetorials. Breu defines tweetorials as "a collection of threaded tweets aimed at teaching users who engage with them" [11]. We narrow and slightly shift this definition to be "a collection of at least 5 threaded tweets aimed at teaching users one main concept". We remove "who engage with them" as engagement on Twitter is known to be correlated with a user's following [55], and we do not believe that tweetorials need to be written by those with a large social media following. And we add "one main concept" to focus on Twitter threads that are actively explaining a concept, rather than listing facts about or simply discussing a subject area. Additionally, these tweetorials should not only adhere to our definition, but should also exhibit a minimum level of writing quality. To this end, we focus on selecting tweetorials that we find to be **clear**, by which we mean able to be understood by a general audience, and **engaging**, by which we mean interesting for a general audience to read.[4] Finally, we point out that the judgement of writing quality is inherently biased towards the preferences of the reader. Thus, we do not intend these tweetorials to represent some objective idea of the "best" tweetorials, but rather to be a human-curated sample that aids our understanding of how authors are communicating complex material on Twitter. Given the difficulty of collecting tweetorials (discussed below) we kept all tweetorials that met our criteria, regardless of their engagement metrics (number of Retweets, etc.).

3.1.2 Preliminary data collection. Finding tweetorials in the wild was extremely difficult. They are not tagged or marked in any way that let us search for them, nor was there any way to automatically detect if a tweet, of the hundreds of thousands of tweets published each minute[5], was likely to be the start of a tweetorial. Given the amount of browsing that finding tweetorials required, in this preliminary data collection we collected any threads that looked like they may be tweetorials. In section 3.1.3 we outline how we then read through these threads more carefully and curated a selection that met our requirements.

We started with a seed set of 48 Twitter threads. These were found by all authors of the paper noticing and collecting potential tweetorials that came up in their personal social media feeds. During this time, we discussed and refined our shared understanding of the defining features of

[3] https://twitter.com/GeneticJen/status/897153589193441281

[4] In our collection process we do not know the intentions of the author; given the prevalence of scientists using Twitter in an academic context, and the varied audience that Twitter users both garner and imagine, it is likely many tweetorials are serving multiple purposes, such as communicating expertise to colleagues while simultaneously educating those outside their field. That said, we collect and study tweetorials that seem readable and enjoyable for a general audience, as we are interested in tweetorials as a form of scientific outreach.

[5] https://www.internetlivestats.com/twitter-statistics/

tweetorials, and we were able to note common tweetorial authors, as well as locations where tweetorials were often cross-posted.

To collect a larger number of potential tweetorials, we first created a list of domains to use as search terms[6]. This list included domains from the social sciences and humanities as well as the sciences and engineering, as we believe that the explanatory strategies used in all domains are relevant for science communication. Using a reference list also ensured we were not biased towards domains we might personally be interested in. We then used three techniques every day over the period of the 3rd to 31st of August, 2020 to find potential tweetorials for our collection:

(1) We created a Twitter account that followed users who either had written tweetorials previously, or who tweeted about their area of expertise. Each weekday, one person spent at least 15 minutes browsing the feed of this Twitter account. Every week we added accounts that had come up on the feed that seemed likely to write tweetorials. By the end of the month this account followed 423 users.
(2) We used the Thread Reader App[7], which is a collection of threads that any Twitter user can add to in order to view a thread as a stand-alone webpage. Each day, one person searched their collection of threads for the domains in our reference list.
(3) Similar to above, we used Threader[8], which at the time had a curated list of new Twitter threads on their webpage. (This feature now appears to be deprecated.) Each day, one person looked over this list.

Anytime we came across a thread that might be a tweetorial, we added it to a list, which included our original 48 potential tweetorials. At the end of this process, we had 224 Twitter threads.

3.1.3 Curation of tweetorials. From our preliminary collection of 224 Twitter threads, we wanted to curate a set of tweetorials. These tweetorials would strictly follow our definition of "a collection of at least 5 threaded tweets aimed at teaching users one main concept" while also explaining their concept in a **clear and engaging** manner. Since what is "clear and engaging" can differ between people, we included a professional journalist, two undergraduate students who are studying both an engineering and humanities discipline, a Computer Science PhD student studying writing technology, and a Computer Science professor studying computational design in our collection team. We had at least two people from the team read and discuss each thread before deciding whether or not to include it in our collection, and rejected threads were assigned a reason for rejection. Given this, we selected 46 Twitter threads (21% of collected threads) that met our criteria.

Fifty-four percent of the threads were rejected for not conforming to our definition of tweetorials, for example instead of explaining a concept it simply listed facts about a subject or told a personal story with no clear explanatory goal. 13% were rejected for being unclear or not engaging. The remaining 12% were rejected for a variety of reasons such as having been deleted at some point during the collection process or potentially plagiarizing a blog post from a different user.

3.2 Thematic Analysis

Like any piece of science writing, tweetorials can be decomposed into the lede, body, and conclusion. We consider the first tweet to be the lede, the last to be the conclusion, and all remaining internal tweets to be the body. Although all three components intertwine–the lede often sets up the start of the body as well as the conclusion–we first study each separately, before looking at how they relate to each other. For each component, we employed a theoretical thematic analysis [10], guided by our

[6]Our list included: computer science; climate science; history; politics; neuroscience; medicine; biology; evolution; linguistics; math; physics/astrophysics; literature; art; architecture; anthropology; engineering
[7]https://threadreaderapp.com/
[8]https://threader.app/

knowledge of the science writing literature, to select themes relating to our research question. We reviewed our dataset as a team over the course of many months, looking for repeated patterns and discussing the similarities and differences between the tweetorial patterns and what we typically see in a newspaper article, opinion piece, or feature story. We focused on identifying strategies that are relevant to the communicative purpose of the component. As we had a relatively small dataset of only 46 samples, once we developed the themes, two authors together annotated each tweetorial with any strategies it exhibited (for each the lede, body, and conclusion).

3.3 Findings

3.3.1 Data description. We begin by describing the tweetorials in order to contextualize our analysis of their structure and strategies. Though we did most of our collection in August 2020, 35% (count=16) of the tweetorials were posted prior to 2020, with two being posted in 2017. (See Figure 2a.) Note that prior to December, 2017, tweets were limited to 140 characters, whereas they are now limited to 280.

Our dataset includes 40 unique authors, with 3 authors writing 2 tweetorials in the dataset and 1 author responsible for 4 of the tweetorials. The fact that 36 of the authors are only responsible for one tweetorial in our dataset suggests that writing tweetorials isn't necessarily a huge focus for many of the authors. One of the authors responsible for 2 of the tweetorials (@tony_breu) has written about tweetorials for the academic community [11, 12]. We want to note that just because an author appeared only once or a few times in our dataset does not mean they have not written more tweetorials.

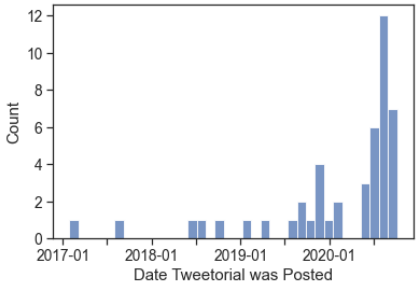
Most tweetorials are between 5 and 20 tweets in length, with a median of 14 tweets (min=5 tweets, max=32 tweets; see Figure 2b). This translates to an average word count of 564 per tweetorial (min=210 words, max=1377 words). 56.5% of tweetorials make use of media at some point in the tweetorial.

Looking at just the first tweet of each tweetorial, there is a wide range of Retweets, between 7 and 27.5k (median=818.5 Retweets). As seen in Figure 2d, there appears to be a "sweet spot" of between 400 and 800 words where the tweetorials in our dataset get the highest number of Retweets, which is slightly below the median for Retweets generally. We found that Retweets tracked closely with Likes (see Figure 2e), which makes sense if you consider both to be a measure of popular engagement. However, the number of Followers an author had did not track closely with Retweets (see Figure 2c), despite previous work which found Follower count was highly correlated with Retweets [55]. This suggests a tweetorial author need not have a large social media following to write engaging tweetorials.[9]

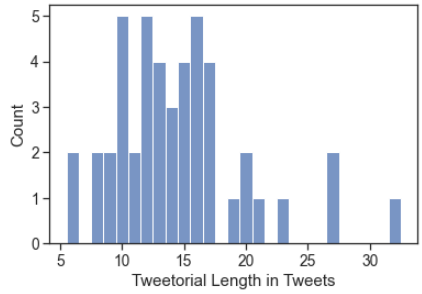
In order to get a general sense of the topic distribution, we assigned high-level topical tags to all the tweetorials; see Figure 2f for all topics. Most of our tweetorials are about *politics, history & business* (count=19), with *health & the body* being the second most prevalent topic (count=12). Note that we tried to collect tweetorials from every discipline, so this distribution is not a random sample but rather the result of actively trying to create an even distribution.

3.3.2 Analysis of lede. We wanted to understand what rhetorical techniques are used in tweetorial ledes, and how these techniques either align with or differ from typical lede recommendations. We consider the first tweet of a tweetorial to be the lede, as users often only see the first tweet in a tweetorial in their feed and are required to click "Show this thread" to view the entire tweetorial (see Figure 5). For this reason, we believe that the requirement of the lede to entice the reader is especially strong with tweetorials.

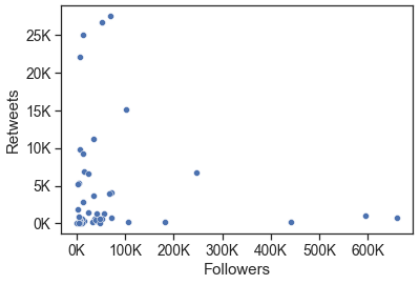
[9]We chose not to do a statistical analysis on Retweet, Like, and Follower data as the relations between these measures are not central to our research question, and our sample is not necessarily representative of all tweetorials.



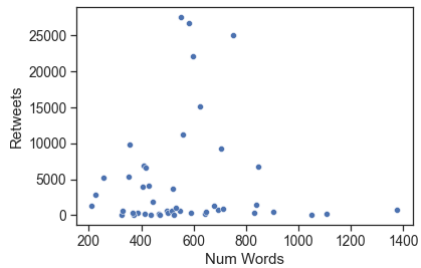
(a) Most tweetorials we collected were posted in mid-2020, though some were posted as early as 2017.



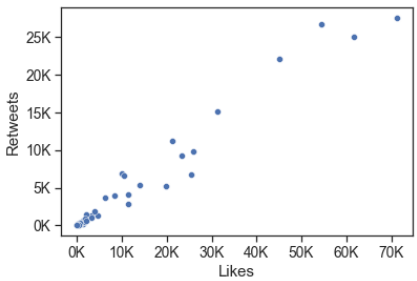
(b) The median length of tweetorials is 14 tweets. The corresponding average word count is 564 words.



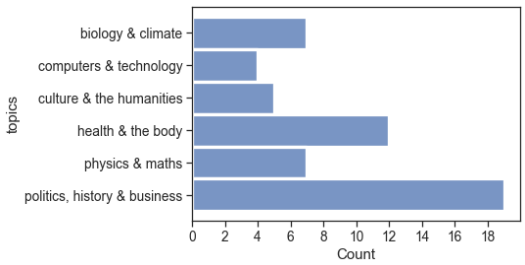
(c) The number of Followers a user had does not predict the number of Retweets the first tweet in a tweetorial received (at the time of collection).



(d) Tweetorials with an average number of words tended to get more Retweets that those that were much shorter or longer.



(e) The number of Retweets the first tweet in a tweetorial has tracks closely with the number of Likes (at the time of collection).



(f) Our collection of tweetorials is dominated by those relating to *politics, history, and business*, though we were able to collect tweetorials across a broad range of scientific and engineering domains.

Fig. 2. Graphs describing general characteristics of our curated set of tweetorials.

We developed the following themes for lede techniques; examples of each theme can be found in Table 1. Note that a given lede may use multiple, or none, of these techniques.

- *Time Peg*. Prevalence: 48%
  In this technique, the author refers to a recent event that motivates why they will discuss this topic now. This is a common traditional science writing technique, but in tweetorials the recent event is often very personal, for instance referring to a discussion with a friend,

Table 1. Techniques in the Lede

Code	Definition	Example
Time Peg (prevalence: 48%)	The author refers to a recent event that motivates why they will discuss this topic now.	My university just announced that it's dumping Blackboard, and there was much rejoicing. Why is Blackboard universally reviled? There's a standard story of why "enterprise software" sucks. If you'll bear with me, I think this is best appreciated by talking about... baby clothes!
Correct the Record (prevalence: 32%)	The author refers to a discussion or viewpoint they will correct or contrast.	1. All this talk about opposition research tonight is driving me nuts because so many people are getting it wrong (not Kyle). This is an area I know well, I got my training as a oppo researcher many years ago, I have also commissioned, disseminated, and received a ton of research
Appeal to Authority (prevalence: 22%)	The author states why they have authority to speak on this topic.	EVERYTHING YOU NEED TO KNOW ABOUT "2+2=5". As a former mathematician, I have things to say. 1/ 🧵
Intriguing Question (prevalence: 15%)	The author poses a question to the reader, but does not answer it.	1/ "Why do my fingers get all wrinkly when I take a bath?" This was the question my 3-year-old daughter asked me recently after bath time. I thought for a minute, then realized I didn't have a clue. The explanation is so much cooler than I had expected...
Counterintuitive (prevalence: 7%)	The author notes that there is something counterintuitive or unexpected about a subject.	I've been watched the landscape of my childhood burn with an aching heart, and wondering how much climate change is to blame. Turns out human activity is a major driver of California's wildfires, but not just in the ways you might imagine. (pic: Noah Berger) 1/10

Fig. 3. On Twitter, threads are often displayed with only the first one or two tweets shown; the user is required to click 'Show this thread' to view the entire tweetorial.

whereas in traditional writing it's more likely to refer to a current event, like a recently released book (although tweetorials will also reference current events). Given the fast-paced nature of Twitter, we see this has particularly high prevalence. This technique also overlaps frequently with *Correct the Record*, where the author may use a recent Twitter discussion as their time peg. However, not all time pegs need be correcting the record, instead they could simply inspire the author's interest in the topic.

- *Correct the Record.* Prevalence: 32%
  In this technique, the author refers to a discussion or viewpoint they will correct or contrast. This is especially relevant on Twitter, where authors would refer to a swell of interest on Twitter they observed and wanted to correct misconceptions others had about the topic. This is a particularly useful technique because it builds on existing interest in the topic. It's also a technique that can be difficult to use in other mediums that may be slower to publish. On Twitter, the author can retweet a comment or reference another user in order to more actively engage with an existing discussion.
- *Appeal to Authority.* Prevalence: 22%
  In this technique, the author makes reference to why they have authority to speak on this topic. While this is a common technique in opinion pieces, it seems particularly important on Twitter as anyone can post a thread on any topic. Even if a Twitter user has an established following where people may already know their qualifications, their threads may end up on a random user's timeline through likes and retweets.
- *Intriguing Question.* Prevalence: 15%
  In this technique, the author poses a question to the reader, but does not answer it in the first tweet. It's important to note that these are not rhetorical questions, which generally start a discourse or present the speaker's opinion, but rather are questions a reader may genuinely want to know the answer to. In tweetorials, they work to set up a gap in the reader's knowledge and encourage the reader to keep reading in order to learn the answer. This technique is also used in traditional science writing.
- *Counterintuitive.* Prevalence: 7%
  In this technique, the author notes that there is something counterintuitive or unexpected about a subject, for instance by saying "this is a false dichotomy" or "there's a problem with our understanding". This is related to *Correct the Record*, though it does not always refer to an existing discussion, and correct the records may not explicitly reference the counterintuitive aspect. This is also a common traditional science writing technique. We note that counterintuitive situations are also used implicitly, often relying on the audience's expected understanding of an idea to intimate something unexpected. For instance, one tweetorial refers to the "social construction of crime" which presumes the audience finds this idea counterintuitive. We did not annotate these as counterintuitive as it's very dependent on audience perspective, but it's important to note its prevalence is likely much higher if we counted ledes that used an implicit counterintuitive.

Overall we find these techniques are well-aligned with traditional science writing advice, but exhibit greater instances of the personal. Each technique is more likely to relate to a personal experience, whether it be a personal experience of a discussion on Twitter ("So much anti-science crap on Twitter this morning") or a personal experience than made them think about their topic ("Somebody asked me this question recently"). While this does occur in other kinds of science writing to entice the reader, overall we see the personal as extremely prevalent in the ledes our tweetorials.

3.3.3 Analysis of body. Between the lede and the conclusion is the bulk of the writing. This is where the author explains their main concept and any relevant adjacent information. This is the most varied part of a tweetorial, as authors vary the length and type of details when explaining their main concept, as well as the most difficult, as the concision required from tweets is at odds with the technical depth many concepts require. We first report on a number of traditional explanatory techniques used; see Table 2 for examples.

- *Use of Narrative.* Prevalence: 85%

Table 2. Techniques in the Body

Code	Definition	Example
	Traditional Techniques	
Use of Narrative (prevalence: 85%)	The author structures their tweetorial with one or more series of connected events.	One tweetorial follows biologist Marie Dacke in her experiments on dung beetle navigation. Another walks through the history of Chicago's public housing.
Signposting (prevalence: 72%)	The author explicitly states what is to follow, or otherwise outlines the structure of their explanation.	SECONDLY 📣📣📣📣📣📣📣📣📣📣 Neo. Pronouns. Exist. Many non binary people use neo pronouns, *not* they/them. Neo pronouns are alternative pronouns people use because language. Is. Allowed. To. Evolve. Examples include: Ze/Zir and Ey/Em
Analogies (prevalence: 46%)	The author uses a more familiar or simpler concept to explain their main idea.	One tweetorial uses the problems of baby clothes to explain the problems with enterprise software. Another uses the familiar concept of fingerprints to explain how hash functions work.
	Tweetorial Specific Techniques	
Subjectivity (prevalence: 80%)	The author references a personal experience or takes a position in some way.	I can only assume there was a systematic operation by the State Department to pressure these other countries to withdraw their asylum offers. Russia just honey badgered it. Honestly, I think we created the Russia issue and it seems odd to focus on it now.
Engaging Conversationally (prevalence: 80%)	The author demonstrates an awareness of their audience by engaging conversationally.	At this point, you're probably like "Kareem, are you for real?" You probably think you've never encountered a calculation that felt weird or unnatural. You have! I'll prove it.
Establishing Credibility (prevalence: 72%)	The author uses references, disclaimers, qualified statements, and asides to build credibility with their audience.	However, there are some COMPLETELY non-exotic explanations as well. These include: (1) Astrophysics (see a recent paper by myself and others like @IbrahimSafa1 https://t.co/naV5yUo01Y) (2) Systematics (which basically means something unaccounted for in the experiment)
Media Use (prevalence: 57%)	The author includes images, GIFs, or videos as part of the tweetorial.	See Figure 4.
Informal Language and Humor (prevalence: 44%)	The author uses colloquial language or references social pools of knowledge or pop culture.	the whole panic around MSG started when a doctor wrote to the New England Journal of Medicine in 1968 OH MAN MY HEAD HURTS AND MY LIMBS TINGLE EVERY TIME I GO TO A CHINESE RESTAURANT, I THINK IT MAY BE ALL THE MSG THEY PUT IN THE FOOD??? 4/?

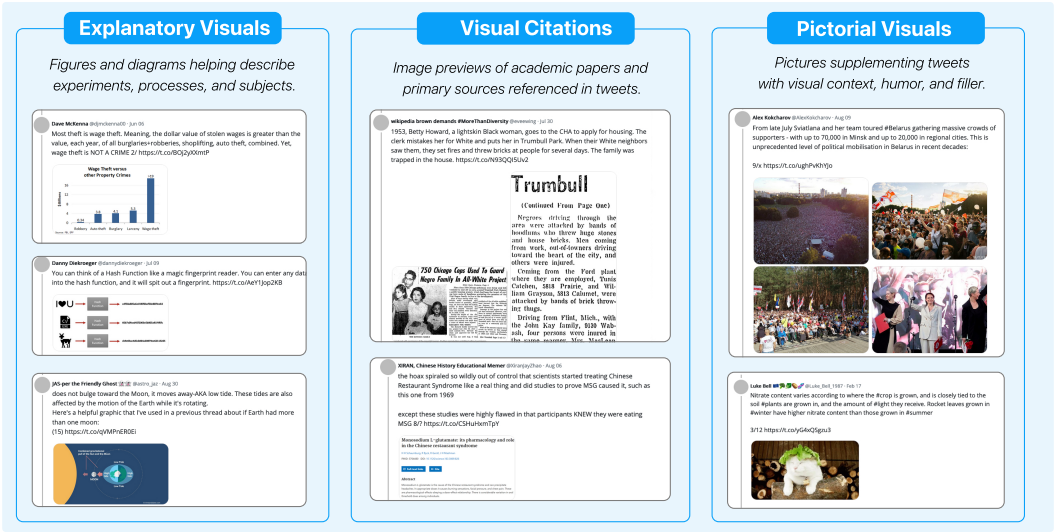


Fig. 4. Tweetorials use media, including GIFs, videos, and polls, in a wide variety of ways. Here we show three common uses of static images.

As advised in traditional science writing, authors often structure the body of their tweetorials with one or more narratives. In tweetorials, we observed that these narratives may come in a variety of forms: discovery narratives (where the author follows a person making a discovery), mechanism narratives (where the author walks the reader through a process), historical examples (where the author articulates a real story from the past), and thought experiments (where the author describes an illuminating hypothetical example).

- *Signposting*. Prevalence: 72%
  Signposting is a strategy where writers explicitly state what is to follow, actively guiding their reader using phrases or outlining the explanation with headers or breaks. In tweetorials we found these phrases do not have to be strictly composed of text; we also found bullet points, numerals, and emojis.
- *Analogies*. Prevalence: 46%
  As advised in traditional science writing, authors utilize analogies to explain their topic through more familiar or simpler contexts. By anchoring readers with concepts they can intuitively understand, writers prime readers with high-level concepts and help them grapple with what is unfamiliar or hard to imagine at scale.

These techniques are well-aligned with traditional science writing advice. Perhaps the most salient difference in tweetorials is how concise the authors are able to be with these techniques. We see this especially in narratives, where a tweetorial may discuss a series of narratives that explain a topic from several different angles, and each narrative is short but informative. We also saw this in the use of numbers and emojis as signposts, which are much more space-effective.

In addition to these techniques, we also found several other tweetorial-specific techniques or themes; see Table 2 for examples.

- *Subjectivity*. Prevalence: 80%
  We found a high prevalence of subjectivity in tweetorials, whether the authors were referencing a personal experience or taking a position in some way. While opinion articles clearly

take a stance, and feature stories may draw on personal experiences, tweetorials were more likely to intersperse their technical explanation with subjective remarks. For example, one tweetorial on Chicago's public housing alternated between lower-case, opinionated speech ("just wanna talk real quick about how we get to 'public housing' as a highly stigmatized, not-so-subtle dog whistle for 'low-income Black people'") and sentence-case, neutral statements ("In 1937 the Housing Act provided federal support to locally-established housing authorities.").

- *Engaging Conversationally.* Prevalence: 80%
  Writers often demonstrated an awareness of their audience by engaging conversationally throughout the body. Instances of this included: acknowledging questions or counterarguments the tweetorial might raise, using rhetorical questions, and acknowledging what emotional or mental state a reader might be led into. For example, in a tweetorial about African Empires and Colonization, the author employs all three devices at once.

  > So when people say, "colonialism benefited Africans," this is why I want to wash their mouths with a soap bar. "But the Africans got technology," you say. "Became modern." You mean like they would've done if they had continued to, I dunno, trade on their own terms?

  When writers engage conversationally, they help readers actively process technical content. This is less common in traditional science writing, where there is a more formal distinction between reader and writer.
- *Establishing Credibility.* Prevalence: 72%
  Throughout the body of the tweetorial, we saw writers using references, disclaimers, qualified statements, and asides to build credibility with their audience. In traditional writing, the credibility of the writer is often implicitly tied to the venue or manner in which they are published (i.e. a newspaper, a book, or a website). However, a tweetorial may be presented to a reader with little to no context. Therefore, credibility has to be constructed on the fly. Writers built credibility by offering statistics, image evidence, hyperlinks, or in-thread bibliographies. Some offered outbound links to articles expanding on their subject or referred to other Twitter users as repositories of knowledge. These methods position the writer as a resourceful expert of their tweetorial content. However, writers do not always have to project their expertise to build credibility. They can also offer disclaimers or qualified statements disclosing the extent of their knowledge, as doing so builds a trust with the reader that they will not be given false information. Informal language may also be considered a way to build rapport with the audience, indicating that the author is being honest and authentic.
- *Media Use.* Prevalence: 57%
  17.4% used visual aids/figures for explanatory purposes, 30.4% used visual citations and 41.3% used visual aids for filler or simple pictorial purposes
  Media presents itself through tweetorials as visual aids, visual citations, and filler. In the context of a Twitter feed, media can help attract reader attention by offering salient breakage points amongst text-heavy tweets. Twitter and traditional writing publications overlap in the usage of images as visual aids. Figures and diagrams help describe experiments, processes, and subjects. When tweetorials refers to subjects in faroff contexts (like the deep sea, ancient history, or outer space), visual aids help readers contextualize and mentally set the stage. On Twitter, images of published papers were also used as visual citations. Some tweetorials used images of historical newspaper clippings as primary sources to back up their explanation. Others used media like memes and GIFs as sources of humor, or as visual filler, perhaps to attract readers who would stop on images as they scroll. In addition, a few tweetorials contained polls, asking readers what they thought was the cause or mechanism of some

aspect of their topic, demonstrating the true participatory nature of tweetorials. This wide variety of media usage is absent from traditional science writing, but quite prevalent in tweetorials.

- *Informal Language and Humor.* Prevalence: 44%
  Informal language and humor refers to instances where the writer uses colloquial language and makes references to social pools of knowledge or pop culture. Such instances include internet acronyms (i.e. 'LOL') , emojis, the omission of sentence casing, all caps, all lowercase, exaggeration, filler words, and punctuated speech. Some writers engage in humor to offer technical details from their field in an unpretentious manner. This technique is highly intertwined with the use of subjectivity, as informal language and humor can make writers sound less objective. This technique, while prevalent in tweetorials, is notably absent from traditional science writing, which tends to be under the demands of publication and peer review, both of which tend to involve dedicated copy editing and adherence to writing standards.

We see that the body of tweetorials make use of traditional science writing techniques as well as add new elements to their repertoire. In particular, the shift toward subjective and informal language is rare in traditional science writing, but features prominently in tweetorials. In addition, media is used in more varied and unique ways, likely due to the constraints imposed by the tweetorial format. We review the implications of a shift towards subjectivity in the discussion section.

3.3.4 Analysis of conclusion. The conclusion of an explanation is not simply a summary of the explanation. It can show how the author has answered any suspense introduced in the lede, place the explanation in a larger context, or emphasize the larger significance of their explanation. In this analysis, when we report the prevalence, we consider only the last tweet in the tweetorial, though the rhetorical act of the conclusion may have spanned several tweets. This was to remove the ambiguity of when the conclusion precisely starts, so these prevalence numbers should be considered in this light.

We found the following themes to be prevalent in tweetorials; see Table 3 for examples.

- *Significance statement.* Prevalence: 28%
  In this technique, the author places the concept in a larger or different context to demonstrate its significance. This is also a common science writing technique, and we see this not only in the conclusion but also throughout the tweetorial if it contains multiple narratives.
- *Summarizes information.* Prevalence: 26%
  In this technique, the author summarizes the main points of their explanation. This is an impressive feat to achieve in a single tweet, and demonstrates the explanatory skills of many tweetorial writers. While this is not typically encouraged in science writing, at least for the conclusion, it does mimic the typical conclusion of an academic paper.
- *Call to action.* Prevalence: 17%
  In this technique, the author requests the reader to take some action. This is a typical technique for opinion pieces, and we see it reflected in tweetorials. Sometimes the call to action is grounded, like requesting the reader read another explanation or support a specific type of business, but more often it's a request for the reader to change their opinion. In this way, we see that many tweetorials are trying to change their readers' views, rather than simply provide the reader with new knowledge.
- *Where to learn more.* Prevalence: 17%
  In this technique, the author points to other resources the reader might be interested in. While this is a common science writing technique, it's notable that the types of resources are quite varied, from other Twitter users to follow, to other tweetorials, academic papers, newspaper articles, or blog posts. This indicates that tweetorials are occurring in a wide

Table 3. Techniques in the Conclusion

Code	Definition	Payoff
Significance Statement (prevalence: 28%)	The author places the concept that the tweetorial explained in a larger or different context.	We think of bio as small and astronomical objects as huge and separate but things interact even at these differences in scale
Summarizes Information (prevalence: 26%)	The author summarizes or revisits the concepts explained in the tweetorial.	That the genetics of intelligence is genomewide, not obviously recently selected and that ethnicity labels are crude, broad groupings across complex human history means genetics has a low - if any - contribution to between ethnic group educational differences.
Call to Action (prevalence: 17%)	The author explicitly asks the reader to perform an action.	ANYWAY, if you insist on going out to eat even now, support your local Chinese restaurants, who have been losing business due to COVID-related racism here's my thread on why you shouldn't scoff at "inauthentic" Chinese food,
Where to Learn More (prevalence: 17%)	The author references organizations, links, or people that readers can use to find more information.	And finally, for a quick explanation of the physics mentioned in the paper in the news, see this great thread by @litgenstein
Refers to Lede (prevalence: 15%)	The author explicitly refers to an aspect of the lede.	So as I watch my home state burn, I see how climate change contributes and how people continue to erect subdivisions in a tinderbox as if it doesn't. 10/10

range of information contexts, and reflects previous work that showed Twitter as a hub for science dissemination [64].

- *Refers to lede.* Prevalence: 15%
  In this technique, the author refers back to what motivated the tweetorial in the first place. This is a common science writing technique, and we see it well-represented in tweetorials.

All these techniques map well to traditional science writing, however, while an opinion piece may end with a call to action, it's rare that a feature article would. In tweetorials, we saw all kinds of conclusion techniques being used. In addition, we saw authors using multiple techniques for a single tweetorial. This demonstrates that tweetorials can serve a wide range of purposes, and uses techniques from a variety of existing formats.

3.4 Summary

We find that tweetorials present unique challenges that traditional science writing does not: the need to hook the reader with only 280 characters, the need to quickly build credibility, and the need to remain true to the personal nature of social media. The techniques we report here are the ways authors respond to these unique challenges.

In this study we sought to answer our first research question – *What writing strategies do tweetorials employ and how do they differ from traditional science writing recommendations?* – by studying our collection of clear and engaging tweetorials. We found that while tweetorials do rely on traditional science writing techniques, the introduction of informal language, increased subjectivity, and unique uses of media all demonstrate the creativity with which authors are able

to be clear and engaging on a platform that requires brevity and often presents its content in a contextless manner.

In the next study we ask how well are scientists prepared to write in this format, and how difficult is it to make use of the techniques we report here.

4 STUDY 2: CHALLENGES OF WRITING TWEETORIALS

In order to empower more scientists to communicate their technical expertise through tweetorials, we want to understand which tweetorial techniques are the most challenging to use. There is a longstanding call to increase communication education for scientists [21], and studies have reported a number of reasons scientists have for partaking in science communication, like ensuring the public is informed about scientific issues, increasing the public's trust in the scientific community, and getting people excited about science [6]. However, it is unclear what skills scientists may lack when it comes to science communication on social media. We ask the following research question:

> *RQ2: What difficulties do science PhD students have when writing tweetorials about their own area of expertise?*

To answer this question we ran a half-day workshop, bringing together PhD students and professional science writers to teach the students about tweetorials and have them write a tweetorial on a topic related to their research. We used the techniques we found in Study 1 to frame the explanation of how to write tweetorials, as well as structure our understanding of the students' tendencies.

4.1 Methodology

4.1.1 Workshop recruitment. On November 20th, 2019, we ran a 3 hour workshop to teach PhD students to write tweetorials. We recruited PhD students from a local university in two disciplines: computer science and climate science. Students were recruited by university-maintained email lists, and were compensated $150 USD for participating. 19 students responded to our call; 4 cancelled due to scheduling constraints, leaving us with 15 participants. The computer science/climate science split was 7/8, and the women/men split was 7/8. Students were asked to provide a short writing sample to ensure English proficiency. Prior to the workshop they were asked to read three tweetorials (which we provided) and list three topics they might write a tweetorial about.

Three professional science writers were recruited as mentors through the authors' social networks; each were professional freelance writers, had been published in venues like the *New York Times, Slate*, and more, had taught science writing to scientists in some capacity, and were active Twitter users, though none had previously written a tweetorial. Each was compensated $2,500 USD for participating. We had two 1 hour meetings with the mentors prior to the workshop. In the first we explained our project and answered any questions they had about tweetorials or the goals of the workshop. For the second, we asked each to write a tweetorial on a topic of their choosing, and used the time to discuss their experience writing a tweetorial and how they might guide someone else through the process.

4.1.2 Workshop structure. The workshop was broken up into two parts. The first part included a 20 minute introductory lecture on topic selection by one of the mentors. Students were instructed to select a topic that would be possible to explain in about 15 tweets, and were told to reference provided examples of tweetorials to aid them in writing. They were then given 30 minutes to draft a tweetorial as they saw fit. The goal of this section was to see how well the students could write tweetorials purely based on examples alone.

The second part started with a 20 minute lecture on writing, where one of the mentors described techniques used to write a tweetorial based on our findings in Study 1. Then the students were broken up into three groups, each led by one mentor. With guidance from their mentor, they

discussed their first drafts in the context of the techniques provided for 30 minutes. The goal of this section was to see what students continued to struggle with even when provided relevant writing techniques. After this, the students had another 30 minutes to revise or continue writing their tweetorial, and came back for a closing lecture.

Before leaving the workshop, students were required to fill out an exit survey. The first section of the survey asked open-ended questions about what was difficult or easy about the writing process, while the second section asked participants to rate on a 5-point Likert scale which parts of the writing process they still wanted help with. Survey questions can be found in the appendix. After all students had left, the facilitators and authors of the paper had a debriefing meeting, discussing common themes or issues that came up with the students and the drafts they had written. All writing from the students was preserved.

4.2 Findings

4.2.1 Students reported most aspects of writing tweetorials were difficult. The first section of the exit survey contained open-ended questions about what was easy and hard about writing tweetorials. With these questions we wanted to understand how the students experienced writing tweetorials, without priming them by listing particular aspects of the writing process. The students reported struggling with a variety of aspects, including assessing what a general audience would know about their topic, making use of a casual tone, coming up with analogies and concrete examples, simplifying complex details, making their first tweet engaging, concluding the tweetorial, and keeping to a structure. In the Likert-scale survey, when asked if they would want less help (1) or more help (5) with certain aspects of the writing process, the average score was over 3 for most of the aspects listed (concluding the tweetorial, writing the first tweet, making a topic interesting, using concrete examples), and overlapped with what they brought up in the open-ended questions. The only aspects with a score lower than 3 were 'choosing a topic' and 'eliminating jargon and ambiguous words'. (A box-plot of these results can be found in the appendix.) Overall, the students reported that most aspects of writing tweetorials were difficult, even when given guidance and support by the mentors.

Despite their reported difficulty, we saw all students improve their tweetorials greatly, and leave with clear explanations of some aspect of their research. Next, we go over how the students actually performed in this task, and whether they were able to make use of the techniques we presented.

4.2.2 Students most easily adopted the 'time peg' and 'intriguing question' lede techniques. We found that when students were presented only with example tweetorials, they wrote ledes that sounded like tweetorials but often missed the key principle that makes tweetorial ledes engaging. For instance, here is a draft one computer science student wrote prior to being presented with lede techniques:

> The lack of memory safety is a very serious problem. Why do we think so?

While they end their lede with a question (common in tweetorial ledes) the question is unlikely to be intriguing to a general audience who may not even know what memory safety is. We found that after the students were presented with lede techniques, they were able to put these techniques into practice. Here is the lede from the same student after being presented with lede techniques, which clarify that an intriguing question must be based on existing knowledge the audience has:

> The lack of memory safety is a very serious problem. People may get discriminated against, spied on, or targeted, due to memory safety vulnerabilities. How is that even possible?

Note that in this second iteration, they include a series of examples that a general audience might care about and change their question dramatically, now asking how memory safety might result in catastrophic events. Even if someone does not know what memory safety is, this lede can trigger a reader to become curious.

In their revised ledes, students made use of either *time pegs* ("On this anniversary of Sandy, let's look back") or *intriguing questions* ("How can we predict the future climate when we missed today's weather?"). Most students included some kind of implicit counterintuitive ("Why do we prefer fake physics in the movies?" implies the reader expects we prefer real physics) but didn't reference it explicitly (e.g. by saying something like "It's shocking that we prefer fake physics in movies"). Possibly because they weren't responding to an existing discussion on Twitter, they did not use the *correct the record* technique. And only one student included an *appeal to authority* in their lede ("As a climate scientist").

Everyone's lede improved after being presented with lede techniques and being guided by the mentors. While any kind of guidance is likely to improve students' writing, we saw that students struggled to replicate the engaging tweetorial ledes with examples alone. Despite these successes with the lede, many students reported that making use of these techniques was difficult, even after receiving guidance from a mentor.

4.2.3 Students overcame organizational struggles by using narrative structures and analogies. We found that when students drafted their tweetorials prior to being presented with techniques, they struggled to structure their writing and often got caught explaining many small details that derailed their main explanation. Most students were unable to finish a whole tweetorial in 30 minutes. However, after being presented with techniques for the body, the students found narratives and analogies helped them stick to their explanation and avoid getting lost in small details.

In addition to using the techniques to structure their tweetorial, the techniques improved the mechanics of their explanation. For example, one computer science student wanted to explain how we are able to demonstrate causal relationships, rather than just correlations. In their first draft they talked about how variables X and Y might be correlated, and asked the reader if that means that reducing X will always reduce Y. However, the abstract nature of X and Y are unlikely to engage readers. In their second draft, they use a narrative about firefighters, and how no one would ever suggest firing firefighters in an attempt to reduce the number of fires. In another example, one climate science student wanted to explain how only a small amount of water connects the Pacific and Indian oceans, and how understanding this is important for understanding the impacts of climate change. In their first draft, they used a lot of numbers to show that only a very small amount of water travels between the two oceans. In their second draft, they used an analogy of connecting two swimming pools through a paper towel tube to help the reader understand the scale of the connection.

In the body of their tweetorial, students made use of *narratives* ("This was discovered by Sociologist Scott Feld in 1991"), *analogies* ("Let's think about weather as someone's mood and climate as someone's personality"), and *images* ("Which of the following animations looks real?") to clearly explain their topic. Despite all students being invested in clearly explaining their work, working with examples alone was not enough to support them in writing full tweetorials.

However, in order for the students to use the techniques we presented, they needed to brainstorm new ideas of how to explain their work. Most students spent time brainstorming, whether they were brainstorming analogies, examples of when someone might interact with their topic, or intriguing historical events. The mentors were instrumental in this, by helping students think outside of the box and giving students feedback on promising ideas.

As with writing ledes, students reported finding and sticking to body techniques difficult. This is a typical problem for experts, who often have so much knowledge at the ready that it can be difficult to leave some information out. P12 explained this clearly when they wrote, "I think that hardest part was that I felt like I had a lot to say ... So it is hard for me to focus in and figure out how to tell one short story that is part of the big picture."

Overall we saw that tweetorials presented a typical science writing challenge to the students: take a wealth of technical knowledge and transform it into an engaging explanation. We saw that students were willing and able to rise to this challenge, and using a taxonomy of techniques helped them move in the right direction.

4.2.4 Students felt uncomfortable using subjective and informal language. The students were confident in their knowledge, so when it came to the technical details, they felt prepared. Most students also felt comfortable engaging conversationally with their reader. Some peppered their tweetorial with questions that led the reader along ("so how do we (formally) account for common sense?") or posed intriguing observations ("But what about the components that are less visible?").

However, making use of subjectivity or shifting into an informal register proved difficult. Almost none of the students used informal language like all lowercase sentences or internet acronyms (though only 43.5% of our tweetorials in Study 1 used explicit informal language). Some students worried an informal tone would decrease their credibility. P1 wrote, "[The hardest part was] knowing how to use a casual tone while still sounding knowledgeable and getting my science message across." Others had difficulty moving between a formal and informal register; P3 wrote, "[One difficulty was] wavering between 'sexy' and 'informative' tweets".

Perhaps more notably, most students avoided the personal details or interjections we found in 80% of the tweetorials in study 1. While some used a personal story in their lede, they were unlikely to reference it again in the body. Although students felt comfortable addressing their audience directly ("So next time someone asks you why you trust climate models") they felt much less comfortable mentioning themselves. The tweetorials they wrote were good explanations that took a technical topic and made it interesting and digestible for a general audience, but they mostly lacked the subjectivity and personality we saw in the tweetorials from study 1.

5 DISCUSSION

5.1 Post-normal science communication and the role of subjectivity in tweetorials

Tweetorials exemplify post-normal science communication, a mode of science communication that has emerged in response to the following societal shifts: 1) the introduction of digital networks, 2) the ideological polarization of society, and 3) the increasing interpretation of scientific results in terms of risk, policy, and political value [14]. Normal science communication assumed a linear handoff from scientists to media to public [14]. Post-normal science communication has renegotiated these norms, such that they now include *advocacy, contextual interpretation of science, participation, and transparency* [14]. The tweetorials we analyzed demonstrate *advocacy* and *participation*, and we found that experts can relay scientific results to the public using narratives, relatability, and subjectivity. These rhetorical strategies help scientists on Twitter present more authentically, frame findings to be engaging and accessible, and establish credibility.

5.1.1 The scientist as an individual and authentic actor. Marwick et. al. defined Twitter as a technology with "a networked audience", where users must perform for multiple audiences and under multiple contexts (i.e. personal and professional) at once. They claim that is Twitter's strength, as it helps encourage "digital intimacy" between users and their imagined audiences [42]. Scientists can leverage "digital intimacy" to directly reach and engage the public, something researchers have

recently argued is necessary in a post-normal science era [23, 42]. As Koivumäki et. al. state, engaging with the public is "to be heard…[to] enter the media stage…be declared competent according to media rules"—and to enter the public sphere as an individual and authentic actor [36].

The shape of discourse changes as scientists enter this new role. Koivumäki et. al. found four digital academic discourse practices: *informing, anchoring, luring, and maneuvering*. Our analysis of tweetorials aligned with these practices. Metaphors and analogies are a form of *anchoring*, the use of humor is an instance of *luring*, and the use of media and emojis are a form of *attention maneuvering*. Koivumäki et. al. noted that science communicators readily accepted these nontraditional techniques when they saw their potential to "humanize science" and help scientific findings achieve greater visibility.

When the scientist becomes a "dialogic actor", they can present science as a story for their audience. Stories and narratives are well established and effective ways to frame science communication [7, 50]. We saw this in tweetorials as well, as 84.8% of our tweetorials employed narratives. Infusing them with informal language, humor, and opinion can optimize tweetorials for engagement as well as help scientists seem more accessible and authentic online.

5.1.2 The struggle to establish and maintain credibility. On Twitter, context collapse is common, as tweets are often encountered without context as to who the author is or what the subject is about [42]. Writers have the burden of convincing readers to not only stop and read their content but also believe that it is credible. Castillo et. al. reported in an analysis of information credibility on Twitter that the use of URLs and tweet length correlated with higher credibility, whereas "questions and exclamations…and the use [of] first and person pronouns" correlated with noncredibility [17]. In our close read of tweetorials, we showed that scientists writing about their expertise employed first person pronouns *engaging conversationally* and *subjectivity* frequently (at prevalences of 80% each), suggesting nuance to their claim that such techniques track with noncredibility.

Credibility is a paramount issue in a platform known to suffer from bots, polarization, and misinformation. It is estimated that 9% to 15% of Twitter's user base may be bots [57]. Others have quantified misinformation with "general public exposure levels at around 30-50%" [62]. In such a landscape, scientists must establish themselves as sources of trust and spokespeople for the scientific process. Our analysis of tweetorials suggests that authors are aware that they must actively build credibility, because most tweetorials used both subjective language and explicit credibility markers.

5.1.3 Tweetorials inherit known post-normal scicomm issues. While we have established that tweetorials are a nascent form of post-normal science communication, we acknowledge that they come with downsides. First, Twitter is not a neutral medium or communication tool. As a complex sociotechnical system, Twitter comes with formal and informal media logics that influence the science communication filtering through its platform. Media logics refer to the "dominant processes, routines, and standardized formats" [1] on platforms. Twitter has formats, or formal media logics, that force science to be pithy and conveyable through 280 character limits and tweet threads. Informal media logics such as platform social dynamics, engagement metrics (i.e. likes and retweets) similarly influence writers. Writers may minimize scientific uncertainties to their audience for the sake of sounding authoritative or credible, an overarching problem in post-normal science communication. Koivumäki et. al. note that these media logics bias authors toward "attention-maximizing [content]" and the aforementioned "individualization" of the scientist [36]. Another downside with tweetorials is that they have the potential to contribute to the polarization of Twitter [20]. How science communication is perceived is highly dependent upon the partisanship of the audience member. Hart et. al. found in a study on Democrats and Republicans that climate

change science communication "activate[d] political predispositions" and "motivated reasonings", increasing polarization [28].

Tweetorials introduce science through the voice of individuals rather than institutions, and this foregrounding of the scientist may both benefit and harm science communication [59]. While we view tweetorials positively as a teachable writing exercise, we also acknowledge that subjectivity can be a double-edged sword, as science is a field the public traditionally considers objective. Tweetorials seem to be a reflection of larger trends, and we hope this paper prompts more research into their impact.

5.2 Opportunities to support informal science writing

5.2.1 Building communities of practice. In a comment to Nature Cancer, Soragni and Maitra explain the value of turning recent findings into tweetorials: "Breaking down the work into 280 character bits is an exercise in scientific communication that renders papers digestible to a broader audience" [52]. We think the word "exercise" is of particular note: tweetorials can be a way for scientists to practice their writing skills while continually informing and building trust with their audience.

Online communities of practice enable individuals to share resources and expertise based on common interests [58]. Kuznetsov and Paulos found that they emphasize sharing, creativity, and learning over profit and social capital [38]. Given that scientists' motivations for communicating to the public rarely include profit or social capital [6], tweetorials and other kinds of social media-based science communication could become a locus for communities of practice for scientists. This seems to be happening with the #medtweetorials community, which popularized the hashtag and created a specific Twitter account (medtweetorials) to retweet all related tweetorials in a specific format. Their focus is specifically on medical tweetorials, and seems to geared towards cross-discipline education, where scientists from disparate medical domains share knowledge. Developing more communities of practice would also aid the study of tweetorials in the future, as the community would provide an access point for collecting a larger set of tweetorials.

5.2.2 Technology to support writers. In study 2 we found that although presenting students with techniques for writing tweetorials was helpful, the students still found applying these techniques difficult. While running more workshops with in-person mentors would be ideal, it is infeasible to provide this kind of dedicated mentoring and feedback to everyone looking to get started writing tweetorials. We believe there are lots of opportunities for technology to support this kind of writing.

Students reported that coming up with analogies and stories related to their topic was difficult. There is exciting work being done on metaphor, analogy, and simile creation that could be used to automatically generate ideas for writers [18, 24, 26]. Although these systems are in early stages of development, they have been shown to produce ideas that writers can then interpret and turn into meaningful rhetorical devices [24]. Jargon detection and simplification [33, 34], automatic specificity measures [41], and techniques to improve the comprehension of numbers in the news [4, 31] are other areas of research that have seen progress and could be used to support writers looking to improve their explanations.

Recent advances in large-scale language models have been shown to be effective encoders of common-sense knowledge [9]. These models have shown promise as potential tools to help novelists with writing stories [16], and could be used as brainstorming devices if fine-tuned on appropriate technical corpuses. For instance, they could generate lists of kinds of people likely to make use of a certain technology, or common uses for a particular scientific concept. These tools could be developed to be web accessible, or even as Twitter or browser extensions such that writers can request support wherever they are writing.

5.3 Limitations and future work

Our set of tweetorials was limited to 46 and skewed by our pre-existing ideas of what represents clear and engaging writing. This could have impacted what strategies we saw well-represented in the tweetorials. The small number also made it difficult to make broad claims about the effectiveness of the tweetorials, or to make any claims about the relationship between the content and engagement online. Additionally, we didn't collect any demographic data about the authors, which might have impacted how they write or the response they received online. Nor did we ask authors about their intentions. For instance, who is the 'imagined audience' [42] for their tweetorials? What are their goals when writing one? These are particularly important questions when considering the impact of subjectivity and authenticity in post-normal science communication.

Future work could also look at collecting a larger set of tweetorials, and asking more pointed questions about the relationship between a tweetorial and its impact: Do certain rhetorical strategies correlate with better understanding or higher engagement? How do tweetorials spread through a community? How do other users respond to tweetorials? This could dovetail nicely with existing work on academic communities talking to each other [40, 47], and could further work that has demonstrated some scientists break out of an academic community and begin talking with a wider audience [13]. Our analysis could also be applied to other datasets, for example Kulgemeyer and Peter's study of explanatory YouTube videos [37], to see how strategies differ across social media platforms. Additionally, we could more rigorously examine how writers and audiences feel about subjectivity with respect to science communication on Twitter. This could involve a larger sampling of Twitter (as aforementioned) or the evaluation of artificially created tweetorials that range from highly subjective to highly objective.

6 CONCLUSION

Tweetorials are a new form of science communication that have the potential to be both engaging, informative, and viral. In analyzing our collection of 46 tweetorials, we found that tweetorials are more likely to include personal details or perspectives than traditional science writing advice suggests. This move towards the subjective in science communication likely has the benefit of making science more engaging to a general audience. However, it's yet to be seen what the consequences of this shift might be in the long term. In a study with science PhD students, we found that students' tweetorials improved after being presented with common tweetorial techniques. Even with this support, students reported that writing tweetorials was a challenging task. We believe that tweetorials are a phenomenon deserving of more attention, as they present more opportunities for scientific knowledge to reach the public.

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A STUDY 2 SURVEY DETAILS

Students were required to fill out a survey immediately after the workshop. Failure to do so would result in withholding the payment for the workshop. The survey was a Google Form, and the first part ('Open-Ended Questions') had to be completed before the second part could be viewed.

A.1 Open-Ended Questions

- Write (at least) three things you found hard while writing your FIRST DRAFT.
- Write (at least) three things you found hard when REVISING.
- Write (at least) three things you learned by the end.
- What was the EASIEST part of writing/revising your tweetorial?
- What was the HARDEST part of writing/revising your tweetorial?

A.2 Likert-Scale Questions

Each question was on a 5 point scale where 1 was marked as "less help" and 5 was marked as "more help". Students were asked, "For each of the following, please report how much help you would want if you were writing a new tweetorial in the future. If not applicable, please leave that question blank."

- Choosing a topic

- Making a topic interesting to non-specialists
- Writing an engaging *first* tweet
- Eliminating jargon or ambiguous language
- Using simple or casual language
- Using concrete examples
- Deciding what the reader will take away (the payoff)

A.3 Responses to Likert-Scale Questions

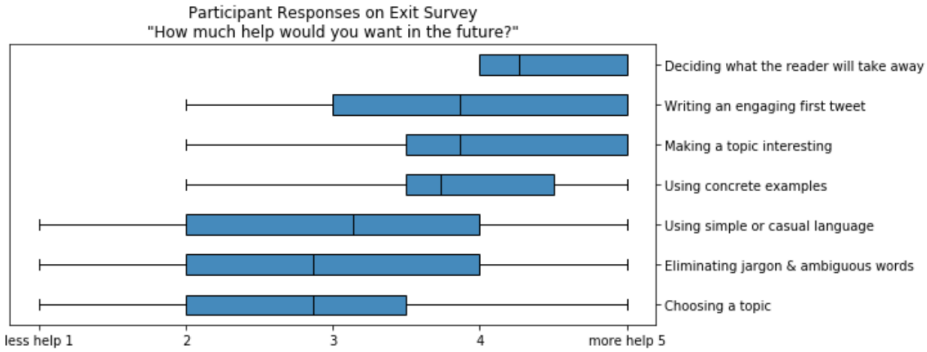

Fig. 5. In this box-plot of responses to the Likert-scale questions in the exit survey, we see that most participants wanted help with most aspects of writing tweetorials. The questions are ordered by the mean response; whiskers mark the max and min responses.

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