

Using representational gesture to enact instants in collaborative problem solving in physics

Emma Teresa Booth^{1,*}, Virginia J. Flood^{2,†} and Benedikt W. Harrer^{3,‡}

¹Berkeley School of Education, *University of California, Berkeley, California 94720, USA*

²Department of Learning and Instruction, *University at Buffalo, Buffalo, New York 14260, USA*

³Department of Physics, *University at Buffalo, Buffalo, New York 14260, USA*



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Embodied forms of representation like gesture have been shown to play an important role in how learners conceptualize phenomena in physics; however, we know little about how students use gesture to capture the idea of *instantaneity*. Drawing on multimodal microanalysis of interaction, we examine how undergraduate physics students use representational gesture to make sense of instants or single moments in time while modeling energy dynamics. Our analysis demonstrates how students use four different forms of representational gesture to capture instantaneity: These include (i) looping and replaying a physical action, (ii) showing a tiny subinterval of time, (iii) freezing a frame of an action, and (iv) marking a boundary location on an imaginary timeline. Implications for physics learning are discussed.

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I. INTRODUCTION

Conceptualizing *time* is essential across all of physics. How people think about and express ideas about time has been explored extensively in the social sciences [1–4], physical sciences [5–8], and by philosophers [9–12]. This interdisciplinary array of studies has shown that across cultures, people use their bodies to make sense of and express ideas about time [13,14]. In particular, people use *representational gestures*, visible motions of the hands and arms that illustrate ideas [15,16], to share and represent ideas about time [4,14,17–20]. Despite the well-explored role of representational gesture in physics [21–31], only a few studies (e.g., Ref. [32]) have explored how students use gesture to represent and make sense of time in physics.

In this study, we investigate how students spontaneously use representational gestures to express ideas about *instants* in time during collaborative problem solving in an introductory undergraduate physics course. The course uses the *Collaborative Learning through Active Sensemaking in Physics* (CLASP) curriculum [33], where groups of students develop models to represent the energy dynamics of various physical phenomena. Our analytic approach draws on microethnography [34–36] and the multimodal

microanalysis of interaction [37–39]. Using video recordings of classroom interactions, we examine how gesture is used as a representational tool by students during discussions of the time interval boundaries of physical processes.

We discovered four types of spontaneous gestures that students use to enact instants during collaborative problem solving. These include (i) looping an interval of action in a physical scenario, (ii) creating subintervals of time, (iii) abruptly stopping a performance of action in a physical scenario, and (iv) using a chopping motion to mark a location in time. We explore the unique affordances each type offers for students' determination of significant instants in modeling energy dynamics.

II. BACKGROUND

The CLASP curriculum is an introductory physics curriculum in which undergraduate students work face-to-face in small groups of 3 to 5 to model puzzling physical phenomena and to answer questions about them. For example, in one activity, groups develop an energy model to explain why a dropped Tic Tac can bounce higher on the second bounce. CLASP discourages memorization and the rote use of equations. Instead, students are immersed in collaborative sensemaking activities to steer their focus to broader concepts and main ideas. In this highly interactive classroom environment, students move between worktables with access to physical equipment and large vertical whiteboards that anchor their conversations. The majority of class time is spent around these whiteboards in small group discussions with minimal direct instruction. Students use novel representations like *Energy-Interaction Diagrams* [40,41] to engage in authentic modeling

*Contact author: et.booth@berkeley.edu

†Contact author: vflood@buffalo.edu

‡Contact author: bwharrer@buffalo.edu

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FIG. 1. An example timeline of a ball being dropped from a hand to the floor marked with suitable start and end points for the model.

practices and sensemaking [42–45]. Energy-interaction diagrams serve as mediators of sociocognitive processes within the group [44,46], supporting discussions and enabling deep engagement with the problem at hand [40]. These features allow CLASP to promote multimodal problem solving [47,48].

When modeling scenarios in CLASP, students often have to identify processes of interest. As part of their representations on the whiteboard, students create timelines—spatial representations of time—on which they must identify suitable start and endpoints for a time interval during which the processes of interest take place (see, for example, Fig. 1). To model the energy dynamics of physics scenarios in CLASP, students identify relevant entities involved in the process under investigation. For the scenario of a hand that drops a ball, the involved entities are the ball, the floor, and the Earth that pulls the ball toward the ground due to its gravitational field. Students must also define the *time interval of interest* by determining start and end points along a timeline. For example, for the scenario described, the beginning might be defined as *just after a ball is released*, and the end as *just after the ball hits the ground*. Because specific transformations and transfers of energy across forms and objects depend on the time interval at hand, the choice of start and end points is crucial for answering specific questions about a physical phenomenon. For example, when modeling a ball being dropped from a hand to the floor from a certain height, choosing the initial and final times to be *just after the ball is released* and *just before the ball hits the floor* means that the hand and floor do not need to be included in the model. This allows students to consider the system as closed (no energy crossing the system boundary), which greatly simplifies the model but restricts the questions about the scenario that can be answered using this model.

The negotiation of instants in time to define a timeline is a key component of a group’s problem-solving process. As physics students in CLASP collaboratively model energy dynamics, their sensemaking processes are intertwined with specific artifacts and representations. However, these representations are not just limited to whiteboard drawings like the energy-interaction diagrams that groups produce. Representational gestures serve students in negotiations about their time interval, making their ideas about

appropriate *instants* in time for their timeline visible to their group, before they decide on and commit these decisions to their energy-interaction diagrams on their whiteboards. Therefore, *gestures about instants in time* play an important role in their process.

III. LITERATURE

A. Time and instants in physics

The idea of *instantaneity* is vital to understanding many concepts in physics. In introductory mechanics courses, for example, students are asked to distinguish between the *instantaneous* speed, velocity, and acceleration of a massive point particle on the one hand and its *average* speed, velocity, and acceleration on the other. Recognizing that instantaneous speed/velocity/acceleration refers to a property of the particle’s motion at a certain *instant* in time and distinguishing this from the average speed, velocity, and acceleration that describe the particle’s motion over a particular *interval* of time is essential to mastering fundamental mechanics concepts. Yet, students often struggle with the distinction between instantaneous and average quantities to describe motion [49–51].

In addition, students also struggle with the difference between a specific *instant in time*, t , and an *interval in time*, Δt , that is bounded by two instants in time, typically an initial time t_i and a final time t_f [50,52]. Perhaps even more challenging for students is the idea of instants in time as the fourth component of a “position 4-vector” that locates a particular event in spacetime, describing not only the spatial location of the event but also the instant in time at which a certain event occurs relative to a prespecified origin [51,53].

The smallest amount of time humans can perceive—with a lower bound of a fraction of a second and an upper bound of three seconds—is known as the “perceptual moment” [54–57]. Historically, representing instants in time was challenging, and there were numerous attempts before the modern concept emerged. Aristotle himself struggled with the idea of instantaneity. He compared it with the concept of “now” that separates the past from the future. However, he redefined it in contradictory ways across his various texts [58,59]. In the end, Aristotle rejected the idea of instants in motion altogether [60].

An *instant* in time is an *idealized object* [61]—a theoretical concept that is part of the “language game” [62] of physics [60]. *Idealized objects* are well-defined abstract entities in mathematics and science that do not exist in the material world but are made tangible and visible through their depiction as visual representations (e.g., a point or a line). In physics, students must learn to flexibly use different representations of idealized objects like instants while avoiding associating any one representation with the object itself.

Problem solving and modeling in physics require moving fluently and creatively between different ways of

representing time. Scholars in science, technology, engineering, and mathematics (STEM) education have highlighted the importance of supporting learners' understanding of the myriad of representations and the relevance of their affordances across different contexts [63,64], especially for idealized objects [61,65]. In this study, we were interested in learning more about the resources students use to represent, discuss, and make sense of idealized objects like instants in time.

B. Embodied metaphor as a tool to make sense of and express ideas about time

In physics education research, the importance of embodied metaphors to conceptualize and express ideas about imperceptible, abstract quantities has been extensively documented [66–71]. For example, experts and learners alike use embodied metaphors to make sense of phenomena related to energy by treating it as a substance-like entity [72–75].

Research across linguistics, anthropology, and psychology suggests that embodied, spatial metaphors are important tools for how people around the world think and communicate about time [2,13,14]. Humans' concrete experiences of space and spatial relationships are used as a basis for understanding the abstract concept of time. People's conceptualization of time through space builds from bodily experiences of moving through the world [76,77].

[Time is space] metaphors [76,77] are embedded in all languages and cultures [3,4,11,78–80]. However, *how* time is grounded in bodily experience varies across cultures [1]. For example, English speakers typically imagine the future unfolding in front of the body because one walks *toward* the future [2,4], whereas Aymara speakers understand the future as not readily perceived and thus *behind* them, out of their sight [4]. To talk about the past, Aymara point in front of them, and to talk about the future, they point behind themselves.

Embodied, spatial metaphors offer useful ways for conceiving of instants. For example, drawing from Aristotle's notion of instants as boundaries, historian Sorabji and philosopher Kretzmann metaphorize a finite interval of time as a long cylindrical shape, like a sausage link, and describe *instants* as the slices that partition the link into smaller intervals [59]. Every time this interval is cut, its subintervals will get smaller and smaller, but in contrast with the slices that divide them (i.e., instants), these subintervals will always have width (i.e., duration).

As a communicative tool with affordances for conveying ideas about space, representational gesture is universally used across cultures and languages to communicate spatial metaphors about time and temporal relationships [2,4,13,14,17–19,81]. However, we know little about how students use embodied metaphor and representational gesture in physics to make sense of the abstract concept of time, and in particular, *instants in time*.

C. Gesture in physics and STEM

Gestures are spontaneous and publicly available expressive actions of the hands [15]. This study focuses on *representational* gestures which are used to illustrate objects and processes—through both literal and metaphorical depiction [82]. Past studies have established that expert physicists use gestures to make sense of abstract physical phenomena together [83,84]. Representational gestures are also an important resource for sensemaking in physics education [24,25,28,30–32,43,48,85–87].

A student might use representational gestures to demonstrate the velocity and trajectory of a ball thrown up into the air [28] or illustrate the grainy texture of a wooden surface to show friction's impact on a sliding object [30]. Students also use representational gestures in physics in more metaphorical ways, such as using the hand to mark a vertical position in the air to convey a specific amount of energy [85,88] or gesturing to show the forces acting at different points of a bridge [43]. Representational gestures allow students to highlight and foreground features of interest [37,38,89,90].

Several studies have also demonstrated the importance of representational gesture for groups' sensemaking about physics together. Gregorcic *et al.* describe the role of gesture in a group's discovery of Kepler's three laws, helping them explore ideas together even though they are still developing lexicons [31]. Steier and Kersting examine students' use of gesture as a medium for imagining spacetime together. In this case, representational gestures make it possible for students to hypothesize and negotiate qualities of time they have not experienced [32].

Representational gesture also makes it possible to switch viewpoints and take different perspectives on STEM phenomena under discussion to explore and model their characteristics and behavior [30,91,92]. For example, students learning about and making sense of computer network package management techniques use gestures to dynamically switch between a more global, network view of information flow and an individual, first-person view of individual information packages as they move through the network [93]. Each perspective has different affordances for conceptualizing the processes involved.

Gesture may also act as a translational tool between representations [86], linking sensorimotor information to discipline-specific representations [27,28,30]. For example, students might enact physical properties of a phenomenon to make sense of trends on a graph [30] or draw from metaphors to tie kinesthetic experiences to symbolic notation [43]. In this way, embodied enactments support the synthesis of abstract and concrete ideas and links between different forms of representations [94–98].

IV. THEORETICAL APPROACH

In this study, we approach gesture as a representational tool that mediates imaginative problem solving—

empowering learners to materialize abstractions, conceptualize the imperceivable, and plan and explore possibilities for action [90,99,100]. Our perspective draws on *distributed cognition* [42,44,45,101] and the idea of *collaborative imagining* [102].

In physics, gesture is a publicly available representation that facilitates sociocognitive processes distributed across social and material practices [27,44,101]. This *distribution* of cognition across the environment in which it is situated treats imagination as a materially mediated and embodied activity [32,38,103–106]. A number of scholars have illustrated how imagining can be a public, collaborative process mediated by gesture and is not solely based on private, mental images [105]. Gesture manifests things not immediately perceived, materializing them for the group to interact with and supporting the continuous achievement of intersubjectivity among individuals [38,90,102,105–107].

Using gesture for public, collaborative processes of imagination is an especially useful tool in problem solving when learners approach problems that involve abstract or imperceivable concepts [103,107–109]. Beyond acting as displays for information, representations—both gesture and other more traditional representations like graphs and diagrams—serve as external tools for conceptualizing and reasoning about phenomena and for coordinating the flow of communication within a cognitive system [24,42,44,101].

In STEM education, *representational competence* relates to an individual's ability to interpret, navigate, coordinate, and communicate understanding through domain-specific representations [110–115]. Furthermore, some researchers have drawn attention to *metarepresentational competence* [116], which encapsulates students' ability to understand when and why certain representations are useful, along with their capability to modify and build representations to serve their contextual needs [116–121]. As a spontaneously created representation, gestures are built around students' immediate problem-solving needs and have affordances for sensemaking and reasoning that are not present in traditional two-dimensional disciplinary representations [100,108,114,115,122].

In this study, we show that physics students spontaneously use gesture as a medium for building and transforming representations of the important *idealized object* of an *instant* in time to support their problem-solving discussions.

V. METHODS

A. Participants and data source

The video data for this study comes from an algebra-based undergraduate physics class that uses the CLASP curriculum at a large, culturally diverse Western U.S. university that is a Hispanic Serving and Asian American and Native American Pacific Islander Serving Institution.

We examined 6 groups of 3 to 4 students (23 students total) completing 9 problems in which they modeled the energy dynamics of puzzling mechanics scenarios to answer questions about them. In each problem, students discussed appropriate timelines for their energy models. The video was recorded with multiple cameras and microphones and was originally collected to understand students' collaborative problem-solving experiences in the course.

We became interested in how students spontaneously use gestures to make sense of instants in time as part of the broader NSF-funded study *DiGEST Physics: Dialogic gesture in collaborative sensemaking in physics* (NSF DUE No. 2201821). For the larger project, the video recordings had previously been coded for all representational gestures. In the process of reviewing these representational gestures, we noticed that students used a variety of different forms of representational gestures when referring to a single instant in time. Students were not explicitly encouraged or instructed to use gestures about instants in time by their instructors. Interested in these spontaneous gestures, we started to collect instances of representational gestures where students seemed to be referring to instants of time to examine the features of these gestures.

B. Data analysis

To refine our understanding of how students were depicting instants of time with their gestures, we first needed to identify different ways people refer to instants of time in *speech*, so we could develop a list of possible *lexical affiliates*. Lexical affiliates are defined as a word or phrase with meanings that closely correspond to a gesture [123]. To develop a list of ways people reference instants in time in speech, we drew on our prior experience with the data, cognitive-linguistic sources, informal survey methods, and also a list of generated possibilities from Microsoft CoPilot (based on GPT-4). This multifaceted approach allowed us to generate a comprehensive set of possible *lexical affiliates* for gestures about instants in time.

First, drawing on linguistics [3,124–126], we identified several different ways people lexically locate instants in time. Speakers can use different temporal coordinate systems to refer to events taking place at specific times: For example, by saying “the initial time is *right after* the ball is released,” the preposition “*right after*” is used to locate “the initial time” with respect to the instant the ball is released from the hand (i.e., a preceding *event*) and occurring as the *next event* in time [3]. Speakers can also use an “extrinsic” coordinate system when they refer to an event as occurring at a particular *point in time*, e.g., “the ball is released *right at* three seconds.” This evokes the amount of time that has passed since the origin of the temporal coordinate system (i.e., $t = 0$) to place the event at a point on a time axis. A third way speakers may refer to an instant is to locate an event with respect to *their own* present time, e.g., “the ball will be released *in* three seconds” [3].

TABLE I. List of possible lexical affiliates for locating instants in time.

Expression	Example
After	“Right after it stops touching the ball”
As	“ As it’s pulled back”
As soon as	“ As soon as he touches the ground”
Before	“It’s just before it hits the ground”
Blink of an eye	“It’s so fast, it passes in the blink of an eye ”
For	“And when it goes down it rests for like a split second right?”
Immediately	“And then it immediately fell down”
Instantaneous	“That’s the instantaneous speed”
Instantly	“It stops instantly once it gets to the top”
Just	“ Just as it’s released”
Moment	“For a single moment ”
Once	“And then once it hits”
Point in time	“At that point it passes equilibrium”
While	“ While the ball is in the air”
When	“ When the hand releases the ball”
Second (<i>also millisecond, microsecond, etc.</i>)	“It’s the same for that whole second ”
Snapshot	“If you’re taking a snapshot of the motion”
Split second	“It goes up and then it technically rests for a split second ”
Sudden	“Then, all of a sudden , it stops”

In addition, we supplemented our list using an informal survey method to poll Instagram users, and we asked Microsoft CoPilot to generate possible ways of referring to an instant in time. Overall, we generated 19 unique possible lexical affiliates for locating instants in time. Our list was refined through multiple iterations, conversations among the research team, and reflection back and forth between the video and the available literature on temporal utterances. We present our final list of possible lexical affiliates in Table I.

Guided by this list of lexical affiliates, we produced a final collection of 36 representational gestures that we identified in our video where students are describing and locating instants in time. Drawing on *microethnography* and *multimodal microanalysis* [34–39], we characterized each representational gesture in this collection. Microethnography provides methods for closely examining the fine details of verbal and nonverbal forms of communication within short durations of interaction in specific settings [37–39]. This analytic approach allows us to closely attend to the public processes of meaning-making participants use with representational gesture and speech. By focusing on representational gestures embedded in short sequences of interaction, we are able to characterize recurrent patterns in form (e.g., hand shape and trajectory

of movement) and examine the affordances particular gestures have for problem solving (i.e., their function).

We repeatedly watched and discussed each gesture where students refer to instants in time and noted patterns in gestural form [34]. This led to the development of a scheme to describe the different ways we observed students use representational gestures when talking about instants in time. Cases where we could not distinguish if the students were describing a moment in time versus depicting a location in space were excluded (e.g., points in space versus points in time). Four recurring yet distinct types based on form emerged, leading to a formal coding scheme which we describe in the findings section of this paper. We applied this coding scheme to our final collection of 36 cases of gestures about instants in time. The coding scheme saturated our dataset [127], with every example fitting into one of the four categories. To check the reliability of the coding scheme, an independent coder analyzed approximately 30% of the cases in the collection, reaching substantial agreement with the original coder, as suggested by a Cohen’s kappa of 0.64 [128].

We chose a specific, representative example of each type of representational gesture depicting instants in time to present in our findings to illustrate the differences of each type and the affordances they have for sensemaking around modeling processes in time. All student names in these examples are pseudonyms, and images have been cartoonized.

VI. FINDINGS

We found 36 representational gestures about instants in time produced by the 6 groups we reviewed as they completed nine different problems. From these, we characterized four distinct forms of representational gesture about instants in time. These included (i) *replay loop of scenario* (9 of 36: 25%), (ii) *subinterval of time* (5 of 36: 14%), (iii) *freeze frame of scenario* (13 of 36: 36%), and (iv) *indexical location on timeline* (9 of 36: 25%). In Fig. 2, we define and summarize these types. We provide a detailed characterization and example of each type in this section.

A. Replay loop of scenario

1. General characterization

Students use *replay loop of scenario* gestures when they repeatedly enact a gesture to show an instant of interest. These gestures depict physical processes and show how objects move through space and interact with other objects. The instant of interest is included in the very short sequence of action. The physical scenario is replayed or “looped” at least twice. For example, a student might enact the instant a ball is dropped by repeatedly opening and closing their fist, as if replaying a video loop of the event.

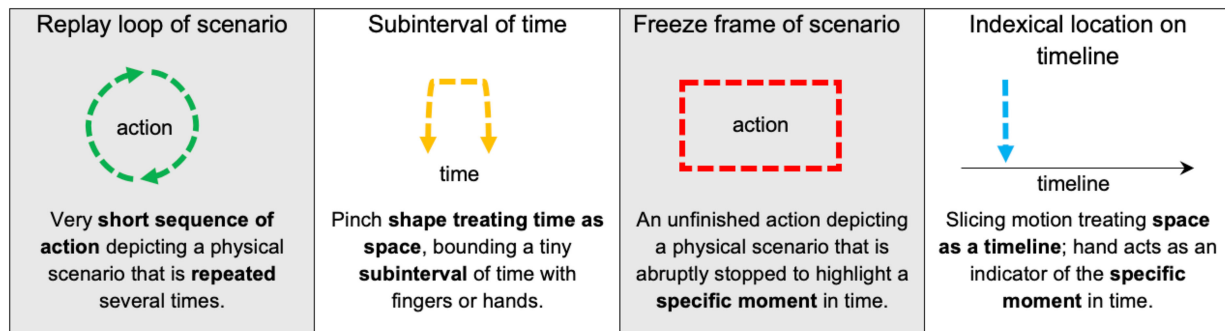


FIG. 2. Illustrations and a brief overview of forms of representational gestures about instants in time.

Replay loop of scenario gestures have useful affordances as groups try to determine the exact instants for their intervals. Students can examine the microseries of events they consider to be relevant to the moment when a boundary of the interval should be defined. As students consider changes in energy states occurring within these intervals of interest, enacting the events leading up to or following a moment of interest may be useful for understanding or demonstrating *why* a specific instant might be relevant to their model [30,93]: They can highlight which specific objects and processes are involved [37,38,86,87].

Replay loop of scenario gestures present opportunities to prolong groups' access to relevant imagery. By repeating the action, they allow students to locate an instant within a brief sequence of events. By repeating a sequence, the gesture mimics the replaying of a very short video clip, giving group members more time to reflect on it. Students can also control the speed and slow down the reenactment of quickly occurring sequences of events as part of their gesture performance.

Replay loop of scenario gestures can also make certain processes more visible to the group. As students use their bodies to reenact an event, they can change certain aspects to convey things at larger scales or emphasize particular features of the phenomena through handshape or form [30,37,89,108]. As a part of modeling energy dynamics, students must identify relevant entities involved in the process. The enlargement or foregrounding of certain components of the event or action may be useful for getting everyone in the group on the same page by highlighting particular features of the action [37,38,90,129]. Such depictions allow students to create close-up views of details they deem important within an event or phenomenon.

Replay loop of scenario gestures can also selectively depict different perspectives of the action [30,84,100]. By taking on different viewpoints of the physical scenario while gesturing, students can depict the aspects of a phenomenon from the perspective of different entities involved in the scenario [30,84,100]. For example, in the scenario of a compressed spring being released and launching a toy car, enacting the scenario from the point of view of the spring or of the car may help students

depict the instant in time they are trying to locate more effectively.

2. Example: Kevin's replay loop of scenario gesture

In Fig. 3, Kevin and his group are trying to explain why a Tic Tac, when dropped on a table, can bounce higher on the second bounce. The group is modeling the energy dynamics of the bouncing Tic Tac, and they have been experimenting with a Tic Tac and observing how it bounces on the lab table. Kevin uses a *replay loop of scenario* gesture to depict the bouncing Tic Tac and the instant it hits the table.

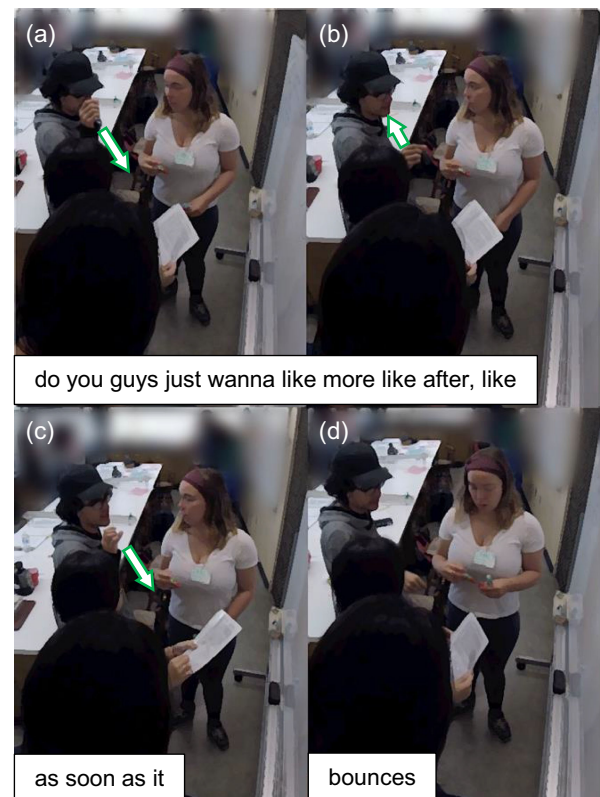


FIG. 3. Kevin (left) performs a *replay loop* of the Tic Tac being dropped, noting the instant it bounces.

Kevin and his group have decided to break their interval of interest into small subintervals to reflect the energy changes that occur throughout the Tic Tac's series of bounces. One group member suggested the instant when the Tic Tac reaches its maximum translational kinetic energy as the initial time of their second subinterval, i.e., right before the first bounce. Kevin responds with a counterproposal, making a pinch shape with his right hand that evokes an imaginary Tic Tac between his fingers. He asks if they want to make it, "more like after," while enacting the Tic Tac falling to the table by dropping his pinched fingers downward [Fig. 3(a)] and bouncing back up [Fig. 3(b)]. Then, he repeats the motion—dropping his hand downward to show the Tic Tac contacting the table again [Fig. 3(c)] and bouncing back upward [Fig. 3(d)]. This time, he describes this action as "as soon as it bounces."

Kevin's ambiguous counterproposal "more like after" does not express in speech the specific instant he is describing, but his gesture enacts the bounce, and he repeats the gesture and specifies in speech, "as soon as it bounces." Kevin enacts the bouncing Tic Tac twice in his *replay loop of scenario* gesture by shaping his hand as if he is holding the Tic Tac as it moves along its path and hits the table. This is not a realistic representation of the phenomenon; however, Kevin's hand shape enlarges the Tic Tac and makes its contact with the table more salient, emphasizing relevant features of the process and the specific moment in time to which Kevin is attempting to draw his group's attention [37]. His repetition highlights this moment in time.

The repeated reenactment of the Tic Tac bouncing off the table may support Kevin in helping his group to focus on and closely examine a specific instant within a rapidly occurring sequence of events. The gesture allows Kevin to foreground certain objects and aspects of the sequence of events, supporting the group's imagination of the imperceivable instant as they consider the appropriate choice for their model [37,100,104,105].

B. Subinterval of time

1. General characterization

Subinterval of time gestures describe situations where students use their hands or fingers to bound a small distance in space to represent an instant in time as a very small subinterval. For example, a student may make a pinch shape with her thumb and index finger while verbally suggesting that an oscillating spring stops for an instant at the very top of its path of oscillation.

Subinterval of time gestures evoke the metaphor of [time is space], visualizing instants in time as a tangible but tiny distance between two fingers. Woodin *et al.* found that people used similar pinchlike gestures to represent "tiny numbers" [130]. *Subinterval of time* gestures use this same spatial metaphor.

Even though a small interval is an inaccurate representation of an *instant*, the *subinterval of time* gestures may

help students narrow the possible location of the instant to a very small span of time [11,54–57,131,132]. Students can use *subinterval of time* gestures to break up longer intervals of interest into small parts for consideration and closely examine those smaller subintervals. This practice is also similar to how physicists use a very small distance and interval in time to find instantaneous velocity (in the common interpretation of dx/dt as a ratio of infinitesimally small intervals of space and time).

Students treat these tiny candidate subintervals of time as instants or possibilities for where the instant is located. We found this particular metaphor was most often used to describe instants or moments in time when objects temporarily "hover" for a "split second" at a particular location before moving. For example, this includes scenarios such as a mass oscillating up and down on a hanging spring "hovering" at its highest and lowest points above and below the equilibrium position, or a car being launched by a compressed spring "hovering" at its initial position for a split second just after the spring is released. While the object technically is only at rest for an instant, it moves so slowly just before and just after that instant that it is nearly impossible to observe this with human perception, and students may view this as a "second" or "split second" but use it like an instant in their models.

2. Example: Jani's subinterval of time gesture

In Fig. 4, Jani's group is creating a story of a physical scenario that matches a set of conditions they have been given. In their story, they are describing a person jumping on a trampoline to match the energy-interaction diagram that specifies the initial conditions of the system as $PE_{\text{elastic}} = 0$, $KE_{\text{trans}} = 0$, $PE_{\text{grav}} > 0$. The students are discussing whether to start their interval at the maximum height of the jump, where they speculate the person's speed is zero ($KE_{\text{trans}} = 0$), and the trampoline is relaxed ($PE_{\text{elastic}} = 0$), right before the person falls back down ($PE_{\text{grav}} > 0$) to match the information in the diagram they have been given. Jani makes a *subinterval of time* gesture [Fig. 4(b)] and asks a group member if the speed of the

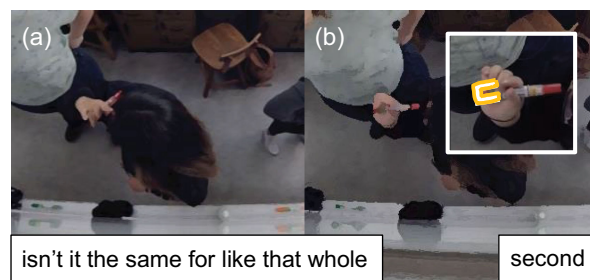


FIG. 4. Jani uses a *subinterval of time* gesture while reflecting on the speed of a person at their max height after jumping up on a trampoline.

jumper would be zero for the “whole second” that the person is at maximum height.

By showing the instant under consideration (the beginning point of their timeline) as possibly being contained in a very small increment of time (the pinch Jani makes is less than a cm wide), Jani provides a candidate subinterval of time within which to locate the instant. During this proposed subinterval, the system does not seem to be changing—it seems to have the same conditions for a finite amount of time, so the initial conditions of the energy-interaction diagram would be fulfilled during the entire duration of this subinterval. Although Jani’s group has not chosen the precise starting point of their interval of interest yet, she has narrowed the possibilities down to a “second” where the conditions of the system are just right to match the initial conditions they have been given. While the pinch gesture evoking a subinterval of time is seemingly at odds with the concept of an instant, it allows Jani to represent for her group the moment in time when the jumper is at rest at the highest point above the trampoline in a tangible way. Using an approximation when an exact value is not available (or needed) is a common and productive scientific practice.

C. Freeze frame of scenario

1. General characterization

Freeze frame of scenario gestures describe situations where students enact a process and then abruptly stop or freeze their gesture at a specific moment in the sequence they are describing. By enacting the process or action and abruptly stopping it, students are able to draw attention to a single “frame” in the sequence. As with *replay loop* gestures, *freeze frame* gestures always depict a literal physical process, representing how objects move through space and interact with other objects. However, instead of replaying the sequence, the idea of an instant in time is conveyed by highlighting the last moment in the sequence of events to show the instant of interest.

By freezing a specific frame or instant in a sequence of events, *freeze frame of scenario* gestures emphasize and

showcase the physical state of the system at an exact point in time. They also allow students to identify and depict the series of events around the instant in time where they propose the interval of interest should start or end. As students are making sense of how a system’s energy changes during a particular interval, depicting events leading up to an instant under consideration may be useful to understand what the state of the system is at that moment in time. The ability to highlight aspects of the process [37,38,89,90] that are relevant to the state of the system is a productive affordance of *freeze frame* gestures that groups can exploit as they determine their interval of interest. The enactment of a small, selective span of time allows students to observe subtle differences between “frames” that are more difficult to perceive when looking at the actual phenomenon itself. Slowing processes and representing them in gesture may also support the group in imagining a discrete instant in time as it is embedded in a continuous process [30]. Finally, students can also hold this last “frame” gesture for an extended period of time, which allows for the group’s prolonged consideration of this specific state of the system [133].

Much like *replay loop* gestures, *freeze frame of scenario* gestures can flexibly represent different aspects or components of the phenomena being analyzed [27,30,92]. Gestures can play multiple roles in a single sequence to foreground important aspects or relationships between entities in the model [30,93]. For example, a student might gesture the pulling down and release of a mass on a spring, depicting the hand performing these actions in the scenario, before immediately becoming the moving mass, and freezing the action.

2. Example: Tom’s freeze frame of scenario gesture

In Fig. 5, Tom uses a *freeze frame of scenario* gesture while his group is determining the initial point of their interval when modeling a rock being thrown horizontally off a cliff to determine the final velocity of the rock as it reaches the ground. Initially, Tom’s group is considering including the hand that throws the rock as part of modeling

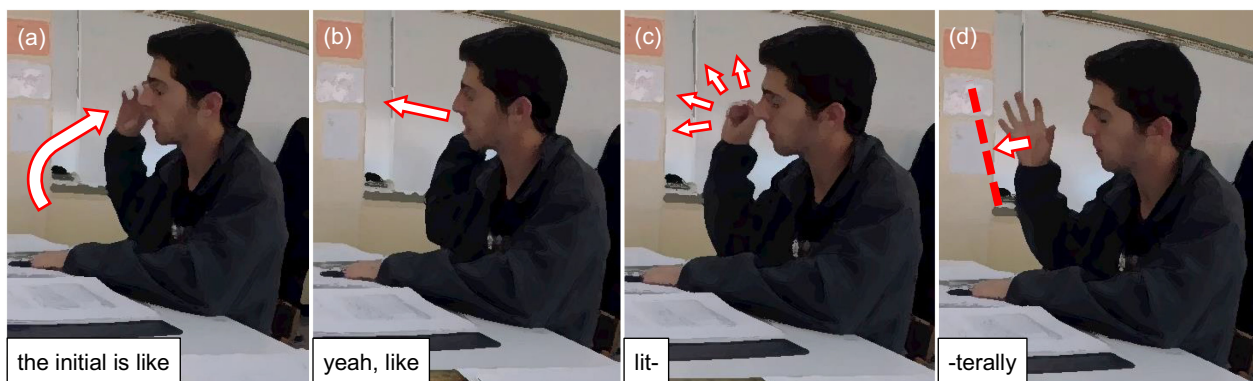


FIG. 5. Tom enacts instantaneity by using a *freeze frame* gesture to highlight the instant the rock leaves the hand.

the process. However, since the hand would be doing work on the system, this requires them to treat their system as an open one, which complicates their energy model and might make it impossible for them to determine the impact speed of the rock.

Tom is explaining to his group the distinction between the instant *just before* the rock is released by the hand and the instant *just after* the rock is released: By choosing the instant *right after* the rock leaves the hand as their initial point on the timeline, the group will still know the initial (release) velocity, but they will not have to include the hand (and the work it does on the rock) in their model. Tom acknowledges that they could choose either instant, but he proposes that using the instant right after the rock leaves the hand will greatly simplify their model. He uses a *freeze frame of scenario* gesture to locate where this specific moment occurs in the sequence of events. We see Tom drawing his arm back as if getting ready to throw the rock [Fig. 5(a)] while curling his fingers into a fist around the imaginary rock [Fig. 5(b)]. He then thrusts his hand forward, starting to open his fist [Fig. 5(c)], and abruptly stops his “throw” with his fingers opened but slightly curved, as if loosely shaped around the rock [Fig. 5(d)] at the point of release.

Using the *freeze frame of scenario* gesture, Tom is able to slow down the process leading up to the release to make the distinction between frames more salient. He holds his hand in the final position of release (a frozen frame) to highlight what the instant looks like. Moments in time, like the instant of a rock’s release, happen too quickly to be seen. The stopped-short action of Tom’s freeze frame highlights the moment in time and allows the group to witness and break down the movement of the hand and the rock into frames, making this instant in time available to reflect on.

The moment after the rapid unfurling of Tom’s fist appears to be the moment he is drawing his group’s attention to, and his change in handshape defines a boundary between the rock’s contact with the hand and its release [134]. This action marks a distinct difference between just before release and just after, illustrating an instant in time as an instantaneous change of state between two frames in a sequence. In this case, the depicted instant divides the process of throwing the rock into a segment during which the hand does work on the rock and a segment during which the hand no longer transfers energy to the rock. Starting from this point allows the group to treat the system as closed, simplifying the model and setting the group up to solve the problem.

D. Indexical location on timeline

1. General characterization

Indexical location on timeline gestures use a flat palm and a chopping motion to mark spatial locations as instants in time. These gestures evoke and mark lines, slices, or

boundaries in space as instants. By marking a point along a timeline or a path of motion, *indexical location on timeline* gestures use the metaphor [time is space] and seem to draw on a metaphor similar to Sorabji and Kretzmann’s slices of time [59]. The chopping motion of *indexical location on timeline* gestures is usually synchronized with verbal descriptions of the physical scenario to specify when the instant of interest occurs during the narrative description of events. For example, when a phrase like “right after” is paired with this type of gesture, it may provide additional information about when the instant in question occurs relative to the reference event [3].

Indexical locations on a timeline have iconic similarities with the horizontal timeline typical for energy-interaction diagrams. They are often performed *perpendicular* to the path of motion of the objects in a scenario. For example, while modeling the energy dynamics of a ball being thrown *horizontally*, a student may make a *vertical* slicing motion in the air in front of them, proposing the moment right after the ball’s release from the hand as the beginning point of the interval on the timeline for their model. However, a student may use a *horizontal* chopping motion to indicate the instant that a mass oscillating on a *vertical* hanging spring passes the equilibrium position.

Indexical location on timeline gestures offer students several affordances for determining and marking the exact instants when an interval should start or end. In particular, *indexical location on timeline* gestures focus attention on single, precise points on a timeline, as opposed to a span of time or a sequence of events. Cooperrider and Núñez describe similar locative temporal gestures, which they termed *placing gestures* [135]. Participants in their study examined a large timeline that presented information about the entire history of Earth and, when asked to convey this history to others, often used slicing gestures to describe the location of events along the timeline. These locative gestures, like our *indexical location on timeline* gestures, draw from the symbolism of timelines by using perpendicular dashes to locate events in time [44,86,101,136].

2. Example: Tatiana’s indexical location on timeline gesture

In Fig. 6, Tatiana uses an *indexical location on timeline* gesture while her group is trying to ascertain which features of a toy car determine what speed the car will be launched at from a toy car launcher. The group is creating comparative models for two toy cars and discussing an appropriate interval for their models. Tatiana proposes that the final time should be “right after” the spring returns to equilibrium, as that is when the car is released and no longer in contact with the spring. To reference and highlight this exact moment in time, she utilizes an *indexical location on timeline* gesture. Tatiana holds her hand in the air with her index finger outstretched and pointed upward as she begins

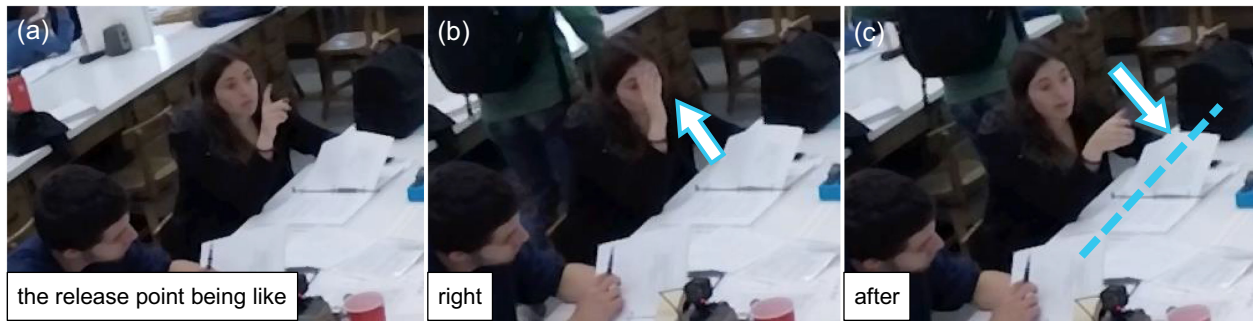


FIG. 6. Tatiana makes an *indexical location on timeline* gesture to point out the instant a launched toy car separates from the car launcher.

her suggestion with, “the release point being like” [Fig. 6(a)]. She then opens and flattens her hand, straightening her fingers as she says, “right” [Fig. 6(b)], and moves her hand downward in a chopping motion, co-timed with “after” [Fig. 6(c)].

Tatiana’s use of the *indexical location on a timeline* gesture makes salient that there is an exact instant in time being referenced; her timing of this motion with her speech increases the precision of her language “right after” to better reflect that she means the exact point in time postrelease. Finally, the vertical movement of her hand may evoke a precise point in time on an imaginary timeline that is superimposed on the physical scenario of the car launcher that the group is analyzing and therefore represents a blend of a position in time and space [24,42,44,137].

Like *subinterval of time* gestures, *indexical location on timeline* gestures evoke a spatial metaphor to represent instants in time. However, the locative metaphor enacted by *indexical location on timeline* gestures provides a higher level of precision, which may be more useful in Tatiana’s case. Tatiana seems to show her group an exact moment in time, where the distinction between a singular point and a small interval is especially relevant.

VII. DISCUSSION

This study contributes to a better understanding of how physics students engage with abstract and complex topics like time using representational gesture, building on previous work in this area [24,25,28,30–32,43,48,85–87,109]. In particular, we examine how undergraduate physics students use representational gestures to enact *instants of time* as they collaboratively discuss and model the energy dynamics of puzzling phenomena. We discovered four different types of gestures about instants that students use when defining intervals of interest for modeling energy dynamics of different physical scenarios. These include (i) *replay loop of scenario*, (ii) *subinterval of time*, (iii) *freeze frame of scenario*, and (iv) *indexical location on timeline*.

Defining instants in time and distinguishing points in time from intervals of time is often challenging for students [52]. From our experience in the world, instants are imperceivable, and even the briefest moment seems to take up a finite amount of time [54–57]. Using spatial metaphors to locate events in time—either with respect to other events or with respect to the origin of a coordinate system—is a useful tool for students to draw on to make sense of instantaneity. Similarly, investigating the state of a system within small intervals of time during which the system does not undergo observable changes is a productive and expertlike practice. Gesture allows students not only to enact the physical scenario and highlight the state of entities and properties of the system at a particular instant in time but also to enact spatial metaphors for time to locate points in time along an imaginary timeline in space and to “prolong” an instant into a small interval of time that allows for easier consideration and understanding. In each case, the gesture makes abstract and difficult-to-describe ideas visible and tangible.

Replay loop of scenario gestures and *freeze frame of scenario* gestures both represent an instant in time with sequences of action depicting events in a physical process. Both these ways of representing instants make it possible for students to imagine where they should place the boundaries of the interval of interest relative to a particular sequence of events. In *replay loop of scenario* gestures, the enactments allow students to elongate the amount of time relevant imagery is accessible to the group by repeating a simulated sequence of events. In *freeze frame of scenario* gestures, students can highlight the exact instant by showing the immediately preceding event and pausing it. Both depictions allow students to foreground relevant entities and processes within the sequence of events and explore different perspectives in the scenario [30,84,100].

Subinterval of time gestures and *indexical location on timeline* gestures use spatial metaphors to represent instants in time. In *subinterval of time* gestures, a very small vertical or horizontal span of time is shown. In *indexical location on timeline* gestures, a specific location along an imaginary

timeline is depicted. These gestural representations are both grounded in the [time as space] metaphor and do not depict literal, physical scenarios as the previous two types do. Instead, these more abstract gestures represent an instant in a more symbolic way and are connected with the timelines students are tasked with creating and utilizing as part of modeling [41]. They may provide an important bridging step for representing the instant on the standard timeline that students create as part of the energy-interaction diagram.

Different forms of gestures about instants may provide different affordances based on where students are in the problem-solving process [27,91]. In particular, *freeze frame* and *indexical location on timeline* gestures more precisely locate instants in time than *replay loop of scenario* and *subinterval of time* gestures. Highlighting a single point on a line or a single frame in a sequence, as done in *freeze frame* and *indexical location* gestures, may be useful when students have precisely located the instant in question in the sequence of events and feel confident in their placement. On the other hand, *replay loop of scenario* and *subinterval of time* gestures depict instants in less exact ways and provide tiny candidate ranges of time within which the instant of interest can be located. *Replay loop of scenario* gestures localize an instant somewhere in a small sequence of events, and *subinterval of time* gestures localize an instant in a very small increment. However, these depictions do not exactly place the instant at a specific point. We conjecture that this lack of specificity may be useful procedurally when students have not decided exactly where the instant should be located and are debating options before committing to one.

We argue that these four different ways of representing instants in time are productive resources for sensemaking about physics. Specifically, the use of gesture to enact instants in time is a form of *collaborative imagining* [38,102,104] and *distributed cognition* [101] that allows students to represent and make ideas about instants publicly available for problem solving and modeling. Being able to model and problem solve in this setting requires creatively developing representations, customized for the needs of the moment. Each of these four different forms of gesture provides unique and effective ways to share ideas about instants. For this reason, we argue students' spontaneous use of these four different ways of representing instants in time with gesture reflects a type of metarepresentational competence [116], in which students skillfully select ways of representing ideas to best communicate their point and fit the situation [117–121,138].

VIII. IMPLICATIONS, LIMITATIONS, AND FUTURE DIRECTIONS

This study offers several implications for instruction in introductory physics contexts. First, encouraging students' use of representational gestures to discuss timelines in

physical scenarios may be beneficial for problem solving and supporting students' engagement in productive disciplinary discursive and representational practices. Deliberately encouraging students to gesture and attend to one another's gestures about instants in time may provide more opportunities for students to build better public consensus as a group about the specifics of the timeline they choose. We also join others [31] in noting the important affordances of in-person, face-to-face instructional settings, such as the CLASP Discussion/Laboratories, which allow students to use representational gestures for sensemaking together. Discussing problems around vertical whiteboards may provide a particularly productive space for negotiating and representing abstract ideas with gesture in physics [48].

Our study presents several limitations. While the four types of *instantaneity* gestures identified in this study saturated our dataset, our study is based on a limited number of participants in a specific regional context (a university in the Western United States). Many previous studies have found cultural differences in how people gesture about time [1,2,4,19,139], and therefore, different ways of representing instants in time in gesture likely exist in different contexts, languages, and regions. Additionally, given that many studies suggest that the conceptualization of time is impacted by cultural artifacts [139–142], the specific representational system of energy-interaction diagrams [41] may play a role in how students use gesture in this setting [47]. Therefore, the collection we present here may not be exhaustive of all possibilities of gesturing about instants in time when modeling energy dynamics of physical scenarios.

Future studies should investigate how different types of gestures about instants in time are used in different STEM disciplines, in different areas of the world, by students from different linguistic and cultural backgrounds, and in different physics curricula. More work is also needed to understand how gestures about instants in time are taken up and interpreted by other group members in dialogic processes of sensemaking together. In addition, future work could investigate how students gesture about instants in time in learning settings outside of STEM, such as history and music, where time and temporality are central. Finally, future studies could investigate whether there are any differences in student understanding associated with the use of particular gestures about instants in time, or whether students' use of gestures about instants in time is connected with longitudinal learning outcomes.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain personal information about research participants. The data are available from the primary investigators of the DiGEST Physics project Flood and Harrer upon reasonable request.

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