# Is this a helpful YouTube video? A research-based framework for evaluating and developing conceptual chemistry instructional videos

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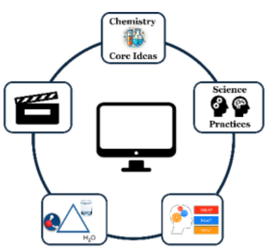
## ABSTRACT

The advent of sites like YouTube has allowed learners to access videos to support their classroom learning. Given the varying quality and content of chemistry instructional videos, identifying and selecting appropriate videos can be challenging for both instructors and students. This article aims to summarize education research important for creating videos to support students' conceptual chemistry learning and identify ways these criteria can be operationalized for use in the framework to evaluate or guide the development of instructional videos focused on conceptual understanding of chemistry topics. The framework helps the user consider the chemistry content of the video through the lenses of the disciplinary Core Ideas, Science Practices, causal mechanistic reasoning, and Johnstone's Triangle. It also includes design considerations from Mayer's Multimedia theory and considerations for accessibility. Finally, we summarize findings and insights gained from using the framework to evaluate as a set of 25 highly viewed or highly relevant YouTube videos related to Le Chatelier's Principle.

## GRAPHICAL ABSTRACT




## KEYWORDS

First-Year Undergraduate / General, Multimedia-Based Learning, Equilibrium, Learning Theories

The advent of sites like YouTube has allowed allows learners to get just-in-time instructional help outside the classroom.[1,2] This has the potential tocan help meet learners'students' unique and diverse needs. However, the instructional quality of chemistry videos on these sites like YouTube varies greatly.[2] Learners searching for videos on their own often lack the sophisticated search strategies necessary to find the most salient instructional videos and the prerequisite knowledge to evaluate their the quality of instructional videos.[3–6] Further, the open contribution model for YouTube being a platform where users can upload content leads to redundancy with potentially hundreds of videos addressing a specific topic. Thus, even with adequate prerequisite knowledge, searching for quality videos frequently requires considerable time. Though research has identified instructional features that support students' conceptual learning of chemistry and important criteria for multimedia learning, these have not been integrated into a research-based framework that can support instructors and researchers in evaluating and developing high-quality chemistry instructional videos. With more chemistry instructorspeople creating videos and more videos available, it is time to start thinking about (1) the quality features of educational videos and (2) how to promote the production of educational videos with these features. This article aims to summarize education research important for creating videos to support students' conceptual chemistry learning, identify ways these criteria can be operationalized for use in a framework to evaluate or guide the development of chemistry instructional videos, and provide examples of the use of this framework for evaluating a set of videos focused on Le Chatelier's Principle.

## BACKGROUND

### Use of Videos to Support Learning

Even before the COVID-19 pandemic forced chemistry instructors to move to remote instruction, Prior to COVID, educational videos had become an important part of education. Learners were increasingly turning to sites like YouTube to support their learning.[1,2,7,8] One study found that 75% (N>300) of survey respondents from two- and four-year colleges reported actively seeking YouTube videos to learn a biology or chemistry concept.[8] During the first month of the pandemic, 84% of the most popular videos were educational and during a sample week, learners accessed YouTube more frequently than the other top ten domains combined.[9] With increased use of blended learning and flipped classroom,[10] the use of ~~it is reasonable to expect increased use of~~ chemistry instructional videos will only increase~~as course supplements or in online course modules~~.

However, the quality of YouTube instructional videos varies greatly. Topic-specific s~~S~~tudies ~~focusing on specific topics~~ have shown that few videos contain useful educational information[11] and ~~that~~ a substantial number of videos may contain information opposing scientific consensus views.[12] Further, studies indicate ~~no or little~~little or no correlation between the informational or instructional quality of the videos and YouTube's quality measures (likes, views, and video comments).[12,13] Additionally, considerations for videos supporting conceptual learning differ from those for videos focused on procedural or skill development. For procedural learning, video choice does not appear to have a large impact, but video choice does have a notable effect on students' self-motivated learning of concepts.[6] The plethora of videos ~~available on a given topic~~, their varying quality ~~of videos~~, and the lack of correlation between popularity and quality make identifying good videos challenging and time-consuming. Thus, a clear set of criteria to consider when evaluating video quality can help instructors identify videos for their students and can support content creators in the development of higher quality chemistry instructional videos.

## General Considerations for Video Design and Evaluation

General criteria for development or evaluation of instructional videos or video explanations have been proposed[14] and several studies have examined the efficacy of chemistry instructional videos[15-20]; however, what is missing is a set of criteria for evaluating the overall instructional quality of conceptual chemistry videos. Although many criteria for effective chemistry teaching in a face-to-face classroom also apply to effective instructional videos, there are also important differences between face-to-face and online learning.[21] ~~One benefit of online instructional videos is on-demand instruction;~~ With videos, learners can engag~~eing~~ with the content when it is most convenient for them and for as long as needed;~~.~~[22] h~~H~~owever, learners need to be motivated to effectively engage with this content and understand what they should learn ~~from the video~~. General criteria for ~~Much of the research on~~ effective instructional videos or video explanations are largely ~~is~~ grounded in the cognitive theory of multimedia learning and cognitive load theory.

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Mayer and Moreno's cognitive theory of multimedia learning states that deeper learning can occur when information is presented both verbally and visually.[23] This theory is built on three assumptions: (1) dual-channel theory – learning is enhanced by simultaneously targeting ~~people have separate~~people's separate ~~channels to receive~~ visual and auditory reception channel ~~information and learning can be enhanced by simultaneously targeting both of them~~; (2) limited capacity assumption - people can process a small amount of information, 5-7 chunks, at once~~any given time~~; and (3) active processing assumption - learning requires active engagement in cognitive processes (e.g., identifying and selecting relevant information ~~, organizing into visual and/or verbal models,~~ or integrating new models with prior knowledge). The limited capacity and active processing assumptions are related to cognitive load theory[24] and the ICAP (Interactive, Constructive, Active, and Passive) framework respectively.[25]

Cognitive load is ~~an~~ important ~~consideration~~ in developing conceptual videos as simultaneous~~presenting~~ visuals and sound ~~simultaneously~~ can exceed a learner's cognitive processing capacity. Accordingly, Mayer identified 12 principles for multimedia learning to reduce extraneous load (cognitive effort wasted on things ~~that do not~~not support~~ing~~ learning), manage intrinsic load (cognitive effort required to represent things in working memory), and optimize germane load (effort required to understand the material).[26]

- **Multimedia:** Videos should include narration and visuals ~~(images, animations, etc.)~~
- **Coherence:** Exclude ~~U~~unnecessary information, graphics, and sounds ~~should be excluded~~
- **Signaling:** Key points should be ~~emphasized/~~highlighted
- **Redundancy:** ~~Use either G~~graphics or text should ~~to~~ complement a spoken presentation
- **Spatial Contiguity:** Related text and visuals should be on-screen close together ~~on the screen~~
- **Temporal Contiguity:** Narration and related visuals should be presented simultaneously
- **Segmenting:** Content should be organized in manageable, coherent chunks
- **Pre-training:** Ensure that learners have essential prior knowledge of key concepts and terms
- **Modality:** Written text should be limited; ~~. Instead,~~ rely on visuals and spoken words
- **Voice:** ~~Use a h~~Human voices are better~~rather~~ than ~~a~~ machine voices

- **Personalization:** ~~Use the first person, avoid formal language, and use~~Use a conversational tone and first person
- **Image:** Minimized ~~Limit the use of a~~ talking heads on the video

These Principles, along with student engagement, serve as the foundation for several video evaluation studies and video analysis frameworks which are ~~have been used to evaluate videos or develop video analysis frameworks with several such studies~~ summarized in a paper by Ring and Brahm.[14] ~~Many of these studies also include student engagement as a criterion in addition to Mayer's principles. This~~Student engagement is inherent in the active processing assumption that underlies the cognitive theory of multimedia learning and is supported by the ICAP hypothesis which postulates that greater engagement with learning materials leads to increased learning.[25]

Other criteria commonly used in video evaluation studies or video analysis frameworks center~~Several groups also included criteria centered~~ on the quality of instructional explanations. In synthesizing several such studies~~this work~~, Ring and Brahm present five criteria categories for evaluating explanation quality, ~~some of~~ which partially overlap with Mayer's Principles.

- **Content:** Should be correct, accurate, and complete
- **Learner Orientation:** Explanations should be targeted, consider the learner's prior knowledge, and connect to other knowledge or experiences
- **Representations:** Analogies, models, graphs, diagrams, charts, etc. should clearly represent the principle
- **Language:** ~~The level of l~~Language complexity should allow learners to translate between domain language and everyday terms
- **Process structure:** Explanations should be structured with coherent argumentation followed by a summary

~~Most of the studies summarized by Ring and Brahm[20] aim to provide research-based recommendations to support instructors in developing and/or selecting videos. Though a few attempted to operationalize criteria in an instrument to measure quality, none focused on chemistry videos. One limitation Ring and Brahm noted in these~~Most studies that used these criteria to develop

**Formatted:** Font: Bookman Old Style, 10 pt video analysis instruments focused on one content area, including was that some criteria were too content-specific criteria and could not be easily adapted to other contexts. Conversely, Ring and BrahmHence, they aimed to developed a more general set of criteria that could be applied to videos over a wide range of topics; yet, that comes with its own challenges. For example, they define technical completeness as "The video explanation is technically complete if no information or subject-specific terms relevant to the topic or the argument are omitted." Using such a criterion to evaluate a chemistry video depends on tThis relies on individualhe evaluator's each deciding what interpretation of what information should be included. For chemistry, research has identified content elements that support student learning which can form the basis of chemistry content specific criteria.

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To date, studies evaluating chemistry videos have not used such chemistry content specific criteria. One study used Mayer's Principles to evaluate chemistry videos finding that of the six elements they coded for, only coherence and organization differentiated videos.[15] Another provided a set of criteria used to peer-review chemistry videos posted to a YouTube channel for Spanish language chemistry instructional videos. However, these criteria include items such as "the author proposes exercises at the end of the lesson" and "the proposed exercises are solved at the end of the video"[16] suggesting a skill development focus. Other studies of chemistry instructional videos have not focused on evaluating video features, but rather on

Most studies analyzing chemistry videos have focused on evaluating student outcome of,for rather than video features, for videos created by the course instructors for specific purposes such as replacing exam review[17] or discussion sections[18] with videos, solving specific organic chemistry synthesis problems,[19] or online tutorials addressing common homework or exam problems on homework or exams.[20] Proposed peer-review criteria for chemistry videos posted to a YouTube channel for Spanish language chemistry instructional videos include "the author proposes exercises at the end of the lesson" and "the proposed exercises are solved at the end of the video"[22] suggesting a focus on skill development videos. One study using Mayer's Principles to evaluate chemistry videos found that of the six elements they coded for, only coherence and organization could be used to differentiate videos.[21] Thus, there exists a need for a video evaluation framework that addresses both important elements of multimedia learning and elements that are more specific to the learning of chemistry concepts. Fortunately, research has identified specific elements such as three-dimensional instruction, causal mechanistic reasoning, and connecting levels of Johnstone's Triangle that support conceptual learning in chemistry and can be operationalized for a chemistry video evaluation framework.

### Chemistry Content Considerations for Educational Videos

Developed by a team of practicing scientists, cognitive scientists, science education researchers, and science and policy experts using a rigorous feedback and revision process, ~~Based on the best available research on student learning in the sciences,~~ *A Framework for K-12 Science Education* (the Framework)[27] outlines a vision for science education grounded in research on how students learn science best. It advocates for ~~puts forth a vision for science education with~~ curricula structured as scaffolded progressions for each of three dimensions: disciplinary core ideas (fundamental concepts that underpin a discipline), scientific and engineering practices (how scientists construct and use knowledge ~~and what they do with that knowledge~~), and crosscutting concepts (tools or lenses used across disciplines for making sense of phenomena).[27–31] Such three-dimensional learning (3DL) promotes the development and use of interconnected knowledge that is more expert-like in nature[27–29,31–34] in contrast to more traditional science instruction and assessment that treats science as a collection of facts and skills,[35,36] frequently resulting in fragmented learning.[28,29,33,37] The 3DL approach actively engages learners in the process of science, such as making predictions and constructing scientific explanations about~~for observed~~ phenomena. In chemistry, an important outcome of 3DL is the ability to explain the macroscopic properties of materials and phenomena within and beyond the discipline.[38] This Causal Mechanistic Reasoning (CMR) requires explanation at a level below that of the phenomenon of interest.[39] For chemistry this generally involves the use of atomic or molecular level motion and interactions to explain observable phenomenon.[40]

The ability to meaningfully connect macroscopic observations with particle behavior is a ~~core~~ challenge for novice chemistry learners recognized in~~by~~ Alex Johnstone's seminal work.[41] He noted that a deep, conceptual understanding of chemistry requires integration of knowledge on three levels: (1) macroscopic - observable by the senses; (2) particulate - interactions and movements of atoms, ions, and molecules ~~and cannot be directly observed~~; and (3) symbolic - representations of macroscopic and particulate using symbols, formulas, equations, mathematical relationships, and graphs. What makes chemistry challenging for novice learners is ~~the difficulty in~~ connecting these three levels.[42–46] If not given appropriate time and opportunity to integrate these ~~three~~ levels of representation, learners build fragmented mental models of concepts.[47]

## FRAMEWORK FOR VIDEO EVALUATION

A valuable framework for the evaluation and development of quality chemistry instructional videos to support conceptual learning should incorporate both aspects unique to the teaching and learning of chemistry content and elements important for multimedia learning. We propose that the evaluation criteria providing the basis of this framework should be informed by 3DL, CMR, Johnstone's Triangle, active engagement and the ICAP framework, and the cognitive theory of multimedia learning. In the following sections, we describe each ~~of these~~ criteria in ~~more~~ detail, outline how these criteria can be operationalized, and provide a summary of findings in applying these criteria to ~~a collection of~~ 25 highly viewed/most relevant Le Chatelier's Principle (LCP) YouTube videos. A complete list of videos, ~~and~~ coding results, and exemplars are included in Supporting Information. General video selection criteria included: over 100,000 views or highly relevant, in English, under 15 minutes, and appearing in one of a variety of related searches.[15]

### 3DLearning - Core Ideas

Chemistry Core Ideas are explanatory and generative concepts fundamental to chemistry that underlie the ~~topics~~ typically taught ~~in a~~ general chemistry topics~~class~~. The Framework defines Disciplinary Core Ideas for K-12 levels. Core Ideas central to chemistry are found in PS1: Matter and Its Interactions and PS3: Energy.[27] At the university level, a set of chemistry Core Ideas (Table 1) were identified by the 3D-LAP (Learning Assessment Protocol) research team and their chemistry colleagues.[29,48] These Core Ideas differ somewhat from those in the Framework though overlap significantly~~there is notable overlap~~.

Since Core Ideas are explanatory and broadly applicable, most chemistry topics have multiple Core Ideas. Hence, any video focused on developing a strong conceptual understanding of a topic should clearly connect one or more of the Core Ideas to the topic. Such explanations can help a learner build a more cohesive understanding of how different chemistry concepts are related. ~~related (through~~

~~common ways of thinking about problems)~~. Table 1 provides the general descriptions of each of the four Core Ideas from the 3D-LAP and~~as well as~~ an additional Core Idea (Particulate Nature of Matter) from the Framework, and outlines how the Core Ideas of Energy, Change and Stability, and Particulate Nature of Matter ~~underlie and~~ are operationalized for the concept of LCP.

**Table 1. Chemistry Disciplinary Core Ideas from 3D-LAP[29] or adapted from the Framework[27] with Operationalization for LCP**

| Core Idea | Description | Operationalized for LCP |
|---|---|---|
| Energy: Macroscopic, atomic/molecular, quantum mechanical | Kinetic and potential energy changes occur when atoms and molecules interact. Energy is released to the surroundings when attractive noncovalent interactions form, and conversely, energy is required to overcome noncovalent interactions. | Changing the temperature causes a shift in an equilibrium by altering the number of collisions that are "successful" in overcoming the activation energy barrier for the reaction. Due to the differences in the activation energy barriers for the forward and reverse reactions, the two processes will be differentially impacted leading to change in the relative concentrations of the reactants and products. |
| Change and stability in chemical systems | Energy and entropy changes, the rates of competing processes, and the balance between opposing forces govern the fate of chemical systems. | Change: "Stressing" an equilibrium system (changing concentrations or temperature) causes changes in relative rates of the forward and reverse reactions<br>Return to Stability: The system "shift to offset the stress" as the equilibrium system returns to a state where the forward and reverse reaction rates are equal |
| Particulate nature of matter | Matter is composed of particles (atoms, molecules, ions). Qualitative and quantitative observations about matter (e.g., Brownian motion, ratios of reactants and products in chemical reactions) can be explained in terms of the motion, interactions, and rearrangements of particles. | Stresses on the system will alter the rates of the forward and reverse reactions by changing the number of collisions and consequently the number of successful collisions (collisions with enough energy and correct orientation). |
| Electrostatic and bonding interactions | Attractive and repulsive electrostatic forces govern noncovalent and bonding (covalent and ionic) interactions between atoms and molecules. The strength of these forces depends on the magnitude of the charges involved and the distances between them. | |

| | | |
|---|---|---|
| Atomic/molecular structure and properties | The macroscopic physical and chemical properties of a substance are determined by the three-dimensional structure, the distribution of electron density, and the nature and extent of noncovalent interactions between the particles. | |

Of the~~Analyzing~~ 25 LCP YouTube videos, seven addressed the Core Idea Change and Stability, but none addressed Energy or Particulate Nature of Matter.~~ we found that few videos contained Core Ideas. Seven addressed Change and Stability but none addressed Energy or the Particulate Nature of Matter.~~ Most videos approached LCP as a heuristic, focusing on predicting equilibrium shifts in response to applied stresses including changes in concentration, temperature, or pressure/volume (for systems involving gases), but not explaining ***why*** such shifts occurred. Though several videos noted that equilibrium systems are composed of forward and reverse reactions, few discussed the rates of those reactions or how stresses altered the ~~rates of the~~ forward and reverse rates~~reactions~~ differently to cause the observed changes to equilibrium system. This is most evident in addressing ~~changes to temperature~~ effects of temperature where "heat" was treated as a reactant (endothermic) or product (exothermic) and predictions were made based on the addition/removal of reactant or product, rather than addressing how changing thermal energy unequally affects the rate of successful collisions for the forward and reverse reactions. Ignoring the connection between ~~forward and reverse~~the reaction rates and their relation to equilibrium state necessitates that the only way to "understand" the topic of LCP is through memorization of a heuristic.

### 3DLearning - Science Practices

The Framework identifies eight Science and Engineering Practices that scientists regularly engage in.[27] Teaching science content through engagement in science practices helps learners~~students~~ understand how scientific knowledge is developed and thus supports the development of a more coherent and connected understanding of science concepts. Although videos do not inherently engage the learner in activities, they can model ~~one or more of~~ the practices. The Science Practices have ~~already~~ been operationalized for classroom instruction, with Engaging in Arguments from Evidence and Constructing Explanation combined.[32] The specific elements for the four most common practices found in chemistry instructional videos are summarized in Table 2. For a video to be considered as containing a science practice, it must meet all the criteria for the practice.

Key for identifying whether Science Practices are incorporated into instruction~~One important commonality between the Science Practices~~ ~~highlighted in Table 2~~ is that each practice starts with an event, phenomena, observation, claim, or question to be explained or investigated. This is~~ key for identifying whether Science Practices are incorporated into instruction~~. ~~Similarly, t~~The last criterion of a practice (providing reasoning) is most frequently missing in instruction. The practices most frequently found in the LCP videos were Analyzing and Interpreting Data and Using Mathematical and Computational Thinking. Several videos met the Analyzing and Interpreting Data criteria by (1) asking what would happen when a certain stress was applied (presenting a situation to be investigated), (2) showing what happened when the system was stressed (providing evidence through observations~~ that could be used~~ to answer the question), (3) connecting color change to direction of equilibrium shift (providing an analysis of the observations), and (4) explaining the results using LCP (interpreting the results). However, most of these videos did not contain a Core Idea or CMR as they ~~focused on~~ describe~~ing~~ what was happening but did not ~~on~~ explain~~ing~~ why it~~this~~ was happening.

**Table 2. Select Science practice and criteria as defined by the 3D-LOP**[32]

| Science Practice | Criteria (all must be present) |
|---|---|
| SP 6: Constructing Explanations and Engaging in Argument from Evidence | • Instruction presents an event, observation, or phenomenon.<br>• Instruction presents or asks instructor/students to make a claim based on the given event, observation, or phenomenon.<br>• Instruction has instructor/students provide scientific principles or evidence (data or observations) to support the claim.<br>• Instruction has instructor/students provide reasoning about why the scientific principles or evidence support the claim. |
| SP 2: Developing and Using Models | • Instruction presents an event, observation, or phenomenon for instructor/students to explain or make a prediction about.<br>• Instruction presents a representation or asks instructor/students to construct a representation.<br>• Instruction has instructor/students explain or make a prediction about the event, observation, or phenomenon.<br>• Instruction has instructor/students provide the reasoning that links the representation to their explanation or prediction. |
| SP4: Analyzing and Interpreting Data | • Instruction presents a scientific question, claim, or hypothesis to be investigated.<br>• Instruction provides a representation of data (table, graph, or list of observations) used to answer the question or test the claim or hypothesis. |

| | |
|---|---|
| | • Instruction provides an analysis of the data or asks students to analyze the data.<br>• Instruction has instructor/students interpret the results or assess the validity of the conclusions in the context of the scientific question, claim, or hypothesis. |
| SP 5: Using Mathematics and Computational Thinking | • Instruction presents an event, observation, or phenomenon.<br>• Instruction has instructor/students perform a calculation or statistical test, generate a mathematical representation, or demonstrate a relationship between parameters.<br>• Instruction has instructor/students give a consequence or an interpretation in words, diagrams, symbols, or graphs of their mathematical results while demonstrating reasoning in the context of the given event, observation, or phenomenon. |

### Causal Mechanistic Reasoning

Chemistry allows us to predict and explain macroscopic observations and the properties of materials using particle motions, interactions, and behaviors.[38] Such explanations, also known as CMR, demonstrate a deep, connected understanding of chemistry concepts. Creating such explanations is challenging for novice learners, and quality conceptual instruction should focus on helping learners develop CMR. CMR can be viewed as answering three distinct questions about a phenomenon: "what?", "how?", and "why?". As such, videos containing CMR focus less on sharing facts or solving algorithmic problems and more on developing a richer understanding of the topic. Developing such reasoning supports learners in ~~more~~ broadly applying their conceptual understanding to explain or predict what happens around new situations or phenomena. Indeed, students can achieve this level of success using~~through the use of~~ carefully constructed curricular materials ~~and~~ with suitable question prompts.[49,50]

For ~~the topic of~~ LCP, CMR could ~~seek to~~ answer the question of "what happens to a system in equilibrium when more reactant molecules are added?" Beyond simply saying that such a system would "shift right" or "the system would make more products", a CMR explanation addresses "how" the change came about, and "why" this ~~increase in collisions~~ leads to the observed shift. The increase in reactant concentration will result in more collisions between reactant molecules and increase the forward rate of the reaction (how). Since the rates of the forward and reverse reactions are no longer equal, there will be an accumulation of more products and reduction in the concentration of reactants until a new equilibrium is established between the forward and reverse reaction rates (why). In this explanation, the reasoning for a bulk measurement (concentration) is explained by particulate ~~the~~

movement and interactions~~ of particles~~, which is the level below the phenomenon of interest. For a given topic, there may be multiple "what" questions that could be addressed. For example, an~~ video on~~ LCP video might similarly answer the question "what happens to a system in equilibrium when the temperature is increased?"

Exploring LCP YouTube videos with more than 100,000 views we did not find any that provided this level of explanation. In fact, it was rare that ~~the idea of ~~collisions were discussed ~~was brought up~~ at all. ~~ ~~This~~The lack of CMR~~ is perhaps not surprising since most videos use LCP as a heuristic. In exploring~~looking at some of the ~~less frequently viewed LCP videos, we found a few videos that ~~provide~~ included CMR. ~~ ~~It is not clear if the disconnect between views and quality/depth of explanation is driven by the typical classroom assessments that do not require how or why explanations or another factor(s).

### Levels of Representation for Johnstone's Triangle

Johnstone's Triangle is an insightful articulation for exploring how chemists think.[41] Johnstone points out that experts move seamlessly between the ~~three levels of ~~macroscopic, particulate, and symbolic levels. Novices, however~~on the other hand~~, tend to reason more along the edges of the triangle and need to gain practice and experience at moving between these levels. Research has shown that learners taught to translate between these levels were more successful in solving general and organic chemistry problems.[51,52] Videos with the ability to include images, animations, simulations, and physical demonstrations can capture and represent each of the different levels in ways that ~~is~~are ~~can be~~ challenging for traditional classroom instruction~~ on a chalkboard or paper~~. The ability to readily incorporate moving images, animations, etc. provide the potential for supporting viewers in the challenging task of developing their own mental models that connect the different levels of representations.[42–46] Johnstone noted that traditionally chemistry instruction has been presented at the symbolic level.[41] However, he advocated for instruction beginning ~~that instruction should begin~~ with the macroscopic level, ~~with ~~things directly observable ~~by learners ~~that learners~~they~~ can connect with their own experiences to help ground newly acquired knowledge. In chemistry, ~~both~~ demonstrations and laboratory experiments ~~are ~~often ~~used to help ~~provide ~~learners ~~such macroscopic experiences. Videos have the same potential ~~to share the macroscopic phenomena ~~but can add in particulate level simulations or animations to help learners make connections between the macroscopic and particulate levels. Thus, videos may be uniquely situated to support learners in making connections between these three levels of chemistry. Yet, novice learners cannot be expected to make these connections on their own. Explicit connections between these levels must be included.

Though~~,~~ all the videos analyzed included symbolic representations, few contained macroscopic representations and particulate level representations were even less common (4/25). This is consistent with an overreliance on the use of the symbolic level in teaching chemistry.[53] Although learning the symbolic level is important since symbols are the language chemists use for communicating and representing chemical concepts,[54] decoding the symbolic language provides extra knowledge demands for students[41] when not explicitly connected to the macroscopic observations or particle interactions they are representing.[54] Developing learners' abilities to provide causal mechanistic explanations requires ~~supporting~~ them ~~in~~ moving between the levels of Johnstone's triangle more fluidly,[41] which is not possible when only focusing on symbolic representations. More positively, when either the particulate or macroscopic levels were present, videos usually made clear connections between multiple types of representations.

### Mayer's Principles of Multimedia Learning

As described previously, Mayer outlines 12 research-based principles for multimedia learning but recent work by Magnone, et al.,[15] suggests that not all these principles are equally discriminating for chemistry YouTube videos. In their evaluation, they focused on six principles: coherence, signaling, spatial contiguity, temporal contiguity, segmenting, and image, noting the greatest variance across videos for coherence (which they combined with Image) and organization (an element of signaling). Additionally, ~~Building on this work,~~ we found the redundancy and multimedia principles were also important distinguishers between videos. Together, these four criteria address Mayer's three core ways to support learning processing by 1) reducing extraneous processing, 2) managing essential processing, and 3) fostering generative processing. Our operationalization of the four criteria and the way that each supports learning are outlined in Table 3.

**Table 3. Operationalization of Mayer's Criteria for Evaluation of Chemistry Videos**

| Criteria | Operationalization of Criteria | Support for Learning |
|---|---|---|
| Text | Text on screen is minimal (ex. Only brief bullet points or keywords if text is used) | Reduces extraneous processing |
| Segmenting | Contains elements that **meaningfully** support student organizing content or identify key ideas (introductory organizer, section heading, summary, guiding questions/topic (for short, focused video only) Key Question: Could a novice learner clearly understand what they should take away from the video? | Manages essential processing by identifying key information |
| Coherence | Content is all relevant to the topic and learning (no music, unhelpful animations, graphics, etc.) | Reduces extraneous processing by removing unnecessary distractors |
| Image | Video almost exclusively involves **meaningful and relevant** images and verbal components AND **images are explained for a novice learner** | Fosters generative processing and helps integrate content with prior knowledge |

Most ~~of the~~ LCP videos we evaluated avoided excessive text and provided meaningful segmenting to help organize the content, often by providing a summary of the content at the end, segmenting the video with meaningful "chapter" titles, or providing a clear overview at the beginning. Videos were less likely to meet the coherence and multimedia principles. Regarding coherence, many videos contain significant asides to the content or had the narrator of the video onscreen for a significant portion of the video, similar to previous reports.[15] These provide additional cognitive distractions that may hinder a learner's ability to focus on the conceptual content. However, it is important to recognize that many videos strive to be both educating and entertaining. Asides and the presence of the narrator on screen may increase interest, something that is ~~certainly~~ critical when selecting and watching videos is a choice. Yet, when ~~trying to~~ learning a new and complex concept, too many or lengthy asides or a distracting presence can impede construction of coherent understanding of a concept, creating a potential dilemma for creators. The key reasons that LCP videos did not meet multimedia expectations were the lack of images to support learning or long video segments with just the narrator talking. This was especially common for older videos of someone giving a lecture in front of a ~~white board~~whiteboard or with handwritten notes, or videos focused on solving LCP problems that showed the chemical equation of the equilibrium system, identified different stresses applied (written text), and then decided what direction the equilibrium would shift ~~(denoted by an arrow or products/reactants)~~.

## Video Content Accuracy and Accessibility

Ring and Brahm included aspects of content accuracy and accessibility in their Content, Learner Orientation, and Representations criteria.[14] In addition to content accuracy (incorrect content or misleading content), which we considered a baseline criterion, we specifically focused on use of analogies and video closed captioning in our framework. Analogies can be very powerful teaching tools, especially for things that cannot be directly observed, like atoms and molecules and their interactions. They can help learners connect the unobservable to something they have prior knowledge or experience with.[55] However, analogies are only useful if the learner has ~~some prior ~~knowledge of the analog example. For example, comparing something to a magnet is not helpful to someone who has never seen or used a magnet. This can be minimized in videos by showing the analogy~~ensuring that any analogy is shown~~ visually instead of ~~rather than ~~just referring to it verbally. Lacking the visual component adds additional cognitive load for those unfamiliar with the referenced process. Thus, our evaluation of analogy use included notes about whether it was presented just verbally or both verbally and visually.

Our framework also assesses one aspect of universal design, Equitable Use in terms of video captioning.[56] ~~Though captioning is often essential for~~In addition to supporting hearing impaired learners, captioning can ~~also ~~help learners watching videos in their non-native language or in learning new technical terms. YouTube automatically captions videos; however, this auto captioning does not include punctuation or capitalization of words. Further, some of the scientific terms used in chemistry videos, e.g., LCP, are frequently auto captioned incorrectly~~ captioned by the auto captioning~~. Thus, our framework includes criteria for evaluating the quality of captioning~~ (no issues, no punctuation or capitalization, miscaptioning of scientific terms, miscaptioning of other words, no captioning or captioning not in English~~).

In our analysis of videos there were a few cases of incorrect content (unbalanced chemical equations or incorrect explanations) but more frequently there was misleading content. For example, six of the 25 videos ~~we evaluated ~~used a balance with equal amounts on each side as an analogy for an equilibrium system. The system was *stressed* by adding or removing something from one side of the balance, and *equilibrium* was restored when the amounts on each side were again equal. This is misleading as it suggests that a system is at equilibrium when there are equal *amounts* of reactants and products as opposed to when the forward and reverse reaction rates are equal. Overall, seven of the 25 videos used some form of analogy with three of them having only verbal reference to the analogy. Interestingly, four of the five videos with over 500k views included analogies. Most of the videos we evaluated relied on auto captioning. However, we also noted that many of the videos by popular content creators were accurately captioned.

### Viewer Engagement

~~Ultimately, it is how learners interact with the videos that will impact their learning.~~ The ICAP (Interactive, Constructive, Active, and Passive) hypothesis predicts that learning increases~~will increase~~ as learners become more engaged with learning materials, from passive up through interactive.[18] ~~Within the ICAP framework s~~Students are classified as passive if ~~they are~~ receiving information (e.g., listening to a lecture or reading a text passage without doing anything), active if ~~they are~~ manipulating information (taking notes, copying a solution, underlining key words), constructive if ~~they are~~ generating additional outputs or products (making connections between topics, solving a problem, explaining, paraphrasing), and interactive if ~~they are~~ dialoguing (debating, discussing, asking and answering questions). Accordingly, ~~Based on this, we expect better learning from~~ videos that explicitly attempt to move the learner beyond the passive interaction of just watching the video better support learning. Although learners~~a learner~~ may opt to take notes or pause and reflect on a topic during any video, this is more likely ~~to occur~~ with videos that ~~specifically~~ explicitly prompt learners to engage with the content~~, frequently by asking them to pause and answer a question or solve a problem~~. In exploring LCP videos, ~~we observed that~~ this sort of prompting was not common (4/25 videos). Although a correlational observation for a single topic, it~~It~~ is notable~~ though,~~ that this ~~it~~ is ~~much~~ more frequent amongst the most highly watched videos (three of the top six most viewed). ~~Again, this is just a correlational observation for a single topic.~~

### Limitations

This framework was constructed to evaluate the potential of videos to support development of *conceptual* understanding of chemistry topics. There are a plethora of chemistry instructional videos

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focused on skill development (e.g. balancing equations, drawing Lewis structures) which can be beneficial to learners but are not the focus of this work.

Using dichotomous choices for each criterion (present or not/high or low) facilitates use of the framework and improves interrater reliability; however, it does not capture gradations of quality for each of the categories. For example, a 10-minute video with only 20-30 seconds focused on a core idea, though very different from one that has the core idea embedded throughout the full length of the video, would both score as having a core idea present. Similarly, some videos scored as low for coherence because they had the narrator on screen for the full time, whereas others had dozens of visually distracting transitions and long asides.

This framework takes a narrow view of engagement, albeit one that is supported by studies that show learners are more likely to watch and comprehend video content when explicitly encouraged to engage though guiding questions, embedded questions, or incorporated into course assignments or assessments. This suggests that it is not just the video that is important, but also how it is incorporated into instruction.[57] However, this framework does not address the entertainment aspect of videos. Wit, humor, a conversational and enthusiastic tone, and personal context are all things that leaners have identified as increasing their motivation to watch videos.[58] Yet, too many side stories or flashy transitions can distract students from the core content.[26]

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## INSIGHTS GAINED FROM USING THE FRAMEWORK FOR VIDEO EVALUATION

The research-based criteria outlined above provide a useful framework for the evaluation or development of videos designed to support conceptual understanding of a chemistry topic. Employing this framework for LCP videos provided an effective lens for evaluating videos. We leave the reader with three specific insights gleaned from the use of this framework and how it can influence thinking about evaluating, creating, and using chemistry conceptual videos.

**The framework outlines important aspects for both consumers and creators to consider regarding the content of chemistry conceptual videos.** To facilitate this, we provide an annotated checklist in the Supporting Materials. Although criteria such as Mayer's Principles or Science Practices can be used without modification to evaluate videos across many chemistry concepts, Core Ideas, CMR, and even Johnstone's Triangle criteria require topic-dependent specificity for ~~users of the~~

~~framework to articulate~~ how these elements can or should be incorporated into a video ~~for each different topic~~. This operationalization for each topic takes time but this advanced planning~~it~~ allows the evaluator or creator to focus on key elements in supporting learners' conceptual understanding and ~~help to~~ ensures the video does not approach a topic from a solely algorithmic perspective. Further, when more than one Core Idea or CMR question is identified for a topic, it could provide a coherent way to break up content for video creators to make several short videos on the same topic.

**The framework can help identify gaps in the existing body of available videos.** Although several videos showed demonstrations of equilibrium systems that change colors as they respond to stresses (meeting the expectations science practice Analyzing and Interpreting Data), most ~~of these videos~~ did not contain a Core Idea or CMR as they focused on describing what was happening but not on explaining why this was happening. This treats LCP as an algorithm to be memorized and applied as opposed to connecting it to collisions between particles. A fundamental explanation of LCP requires talking about particle collisions, which only 3 videos did. However, it is interesting to note that ***none*** of the videos that discussed particle collisions and were coded with CMR included particulate representations. Although when macroscopic or particulate representations were present, there was generally explicit connection between levels, most videos relied solely on symbolic representations. While we anticipate the strengths and areas for improvement will be dependent on the topic, this illustrates how using this framework identified areas of improvement for LCP videos.

**Instruction should be designed to account for students watching videos to support their learning of a topic.** The framework can help instructors identify quality videos to recommend to their students to support learning outside of the classroom. However, many students still choose to search for their own videos. Therefore, using the framework to identify key areas for improvement for videos on a given topic can help instructors focus their instruction. For example, knowing that most videos treat LCP as an algorithm, instructors can focus classroom time on helping students understand the underlying mechanism based on particle collisions. Or knowing that the balance analogy is frequently used in videos, instructors can explicitly address the issues with that analogy in the classroom.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

Evaluation Information for Le Chatelier's Principle for Instructors; video exemplars; checklist for video evaluations (DOCX)

Video evaluations for Le Chatelier's Principle videos (XLSX)

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