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Research Article

A resources-oriented analysis of students' reasoning about electromagnetic waves across contexts

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ABSTRACT

Understanding how students reason about electromagnetic waves (EMWs) remains a challenge in physics education. Rather than viewing student thinking as dominated by stable misconceptions, this study adopts a resources-oriented viewpoint to examine how students activate different conceptual ideas across contexts. Written responses from 37 students to five open-ended questions about EMWs were analyzed, with each answer treated as a student question unit. Through inductive coding, seven conceptual resources were found, including medium interaction reasoning, constancy of EMW speed reasoning, field-based wave generation, energy transfer to matter, and self-propagation in vacuum. A descriptive frequency analysis discovered strong context dependence on resource activation. Different resources consistently dominated different questions, with minimal overlap across contexts. Medium based reasoning was most prominent when comparing wave speeds in different materials, field-based reasoning dominated explanations of wave generation, energy-transfer reasoning dominated microwave-heating explanations, and vacuum-propagation reasoning dominated questions about spread in empty space. These patterns were recurring across many student responses. The findings show that students possess a repertoire of productive conceptual resources that are selectively activated rather than uniformly applied. This study stresses the importance of instructional approaches that support the coordination and refinement of students' existing ideas across contexts.

Keywords: electromagnetic waves, conceptual resources, physics education research, context-dependent reasoning, student understanding

INTRODUCTION

Electromagnetic waves (EMWs) are a central topic in introductory and upper division physics, dealing with key ideas in optics, communications, and modern technologies, as well as advanced areas such as electrodynamics and quantum physics (Griffiths, 2017). In spite of their importance, research has repeatedly shown that students experience substantial difficulty developing coherent understandings of EMW propagation, energy transfer, and transmission through vacuum (Kotsis, 2024; Salele et al., 2025). These difficulties continue across educational levels and instructional contexts, showing that they are not easily resolved through traditional instruction alone (Maloney et al., 2001).

Much of the existing research on student understanding of EMW has focused on identifying misconceptions and documenting improper reasoning (Gray, 2021; Saglam & Millar, 2006). While this body of work has been valuable in displaying common patterns of difficulty, it often characterizes student thinking primarily in terms of mistakes or deficits. As a result, less attention has been given to understanding how students' ideas may be practical and productive in particular contexts.

An alternative perspective, grounded in resources theory, views student knowledge as made of context sensitive conceptual resources that are activated dynamically when students reason (diSessa, 1993; Hammer, 2000). From this perspective, learning includes reorganizing and refining existing ideas rather than substituting incorrect beliefs wholesale. This framework has been applied successfully to the study of mechanical wave propagation, where researchers have displayed common conceptual resources that students use across a range of contexts (Goodhew et al., 2019).

In contrast, few research has examined student reasoning about EMW from a resources-oriented perspective. Given the additional abstraction of EMW, especially the absence of a material medium and the central role of fields, this domain presents a compelling context for extending resources-based analyses (Podolefsky & Finkelstein, 2007; Ryan et al., 2018).

Beyond extending resources-oriented analysis into a new content area, this study aims to refine understanding of how conceptual resources operate in highly abstract electromagnetic (EM) contexts. Unlike mechanical waves, EMWs require students to coordinate reasoning about oscillating fields, propagation without a material medium, and wave-particle descriptions simultaneously (Balta et al., 2022). The present study examines whether students activate different resources across contexts, and also how students coordinate field-based, medium-based, and particle-based reasoning when explaining EMW phenomena. In doing so, the study identifies conceptual resources that are specific to EM phenomena and shows how difficulties may arise from conditional overgeneralization or incomplete coordination of otherwise productive resources.

The present study addresses this gap by investigating the conceptual resources that students use when reasoning about EMW phenomena, including propagation, speed, energy transfer, and transmission through vacuum. In this study, context dependence means that students activate different conceptual resources depending on the specific features of the question they are responding to, even when the underlying physics is related.

Research Questions

RQ1: What conceptual resources do students activate when reasoning about EMW across different conceptual contexts?

RQ2: How does the activation of these conceptual resources vary across different EMW contexts?

RQ3: Which conceptual resources are most dominant within each EMW context, and which resources appear only marginally or not at all?

LITERATURE REVIEW

Student Understanding of Waves in Physics Education

Wave phenomena make a core organizing theme across the physics curriculum, spanning mechanical waves, sound, optics, and EM radiation, and covering later learning in modern physics and technology-related fields. Despite their centrality, decades of physics education research have consistently shown that students experience substantial difficulty developing coherent understandings of wave behavior. Studies across secondary and tertiary levels document persistent challenges in distinguishing between wave motion and particle motion, interpreting wave spread mechanisms, and coordinating key quantities such as speed, frequency, wavelength, and energy (Barniol & Zavala, 2016; Kennedy & de Bruyn, 2011; Tongchai et al., 2009, 2011). These difficulties are not isolated misconceptions but rather reflect deep conceptual tensions that reappear across instructional contexts, instructional methods, and institutional settings. As waves form the conceptual bridge from tangible mechanical systems to abstract EM phenomena, unresolved difficulties at the mechanical wave level can be carried forward, limiting students' understanding of optics, EM radiation, and quantum phenomena.

A central source of difficulty in wave learning lies in the non-object like nature of waves. Unlike particles, waves involve coordinated disturbances that propagate through space without the transport of matter, requiring students to reason simultaneously about local motion, global propagation, and energy transfer. Research on mechanical and sound waves has shown that students frequently coordinate wave pulses using object-based reasoning, attributing properties such as force, momentum, or effort directly to the wave itself rather than to the medium or causal interactions (Hrepic et al., 2010; Wittmann, 2002; Wittmann et al., 2003). This object coordination often manifests in explanations that conflate the motion of the medium with wave speed or assume that increasing 'input' (e.g., flicking harder or adding energy) necessarily increases propagation speed. More recent work has further shown that even when students can recall correct equations, such as $v = \lambda f$, they struggle to combine these relationships conceptually or apply them consistently across contexts (Kryjevskaia et al., 2012; Xie et al., 2021).

The conceptual challenges associated with waves intensify when students encounter EMW, which remove the material medium that often anchors reasoning about mechanical and sound waves. Research on student understanding of light and EM radiation shows that students struggle to reconcile mathematical formalisms with physical meaning, particularly regarding energy transport, propagation in vacuum, and the relationship between fields and waves (Kotsis, 2024; Salele et al., 2025). Visualization studies in wave optics further indicate that representational choices strongly influence how students conceptualize EMW, sometimes reinforcing surface-level reasoning rather than deep conceptual integration (Mešić et al., 2016). Because EMW are essential for understanding modern technologies and advanced physics topics, these difficulties have significant instructional consequences.

Misconceptions and Difficulties in Electromagnetic Waves Understanding

Research on student understanding of EMW has long documented substantial and persistent conceptual difficulties, even after formal instruction. A foundational line of work by the University of Washington Physics Education Group demonstrated that many students struggle to interpret light and EM radiation as moving waves governed by oscillating electric and magnetic fields, rather than as static entities or streams of particles (Kotsis, 2024). Students often fail to connect mathematical descriptions of EMW to physical mechanisms, particularly regarding how energy is transported through space and how fields vary dynamically in time. These difficulties are not confined to introductory students; diagnostic studies in electricity and magnetism have shown that misunderstandings of electric and magnetic fields, such as treating them as forces rather than physical entities, persist well in advanced coursework, undermining later learning about EMW motion (Maloney et al., 2001).

A leading theme in the literature is students' difficulty applying a wave model consistently to EM phenomena. Studies on interference and diffraction of light reveal that students often memorize conditions for constructive and destructive interference without understanding superposition as a physical process (Salele et al., 2025). In these contexts, learners frequently rely on surface level formula use, such as changing wavelength or frequency relations, while lacking a coherent conceptual model of propagation. This formula centered reasoning shows difficulties observed in mechanical waves but is amplified for EM waves due to their abstract nature and the absence of a tangible medium. As a result, students often conflate speed, frequency, and energy, incorrectly assuming that increasing frequency or intensity changes propagation speed, or that EMW require a material carrier to travel through space.

The literature has been highly influential in identifying common patterns of incorrect reasoning and informing curriculum development aimed at remediation. However, it overwhelmingly frames student ideas as misconceptions to be corrected or eliminated, rather than as sensible forms of reasoning in prior knowledge. For example, recent instructional studies addressing EMW propagation difficulties continue to emphasize replacing incorrect ideas through targeted interventions, reinforcing a deficit-based view of student thinking (Pagiatakis et al., 2021). While such approaches have yielded important views, they offer limited guidance on how instructors might productively build on students' existing intuitions. As argued in recent resources-oriented work on mechanical waves (Goodhew et al., 2019), a sole focus on errors obscures the continuity between novice reasoning and expert understanding. This limitation motivates the need for a balancing lens, one that examines how students' ideas about EMW may function as context-dependent conceptual resources rather than isolated misconceptions.

Origins and Foundations of Resources Theory

Resources theory emerged within physics education research as an alternative to deficit-oriented models of student thinking. Rather than characterizing student ideas as stable misconceptions to be replaced, resources theory conceptualizes knowledge as composed of fine-grained, context-sensitive elements, often referred to as resources or phenomenological primitives, that are activated dynamically in response to specific situations (diSessa, 1993; Hammer, 2000). Although early formulations of resources theory often emphasized highly fine-grained knowledge elements or phenomenological primitives (diSessa, 1993), later resources-oriented physics education research has also examined broader clusters of coordinated reasoning that function productively within particular conceptual contexts (Goodhew et al., 2019; Hammer, 2000). In the present study, the identified resources are therefore operationalized as recurring patterns of conceptual reasoning that organize students' explanations within specific EM contexts, rather than as isolated microscopic knowledge elements.

Three core assumptions characterize the resources framework. First, student ideas are assumed to be sensible to the learner: they arise from productive attempts to make sense of physical phenomena and often work well in everyday contexts. Second, knowledge is context-sensitive: the same student may activate different resources in response to superficially similar problems, depending on features of the task, representations, or wording. Third, learning is viewed as a process of reorganization and refinement of existing resources rather than wholesale replacement of incorrect ideas. Conceptual change, from this standpoint, involves stabilizing productive resources, suppressing unproductive activations, and coordinating resources into more coherent and formal forms. This view directly contrasts with traditional misconception models, which typically assume that incorrect ideas are robust, unitary beliefs that must be confronted and eliminated before learning can occur.

A key implication of resources theory is the emphasis on continuity between novice and expert thinking. The same types of resources that students use in informal or incomplete ways are also part of expert reasoning, differing primarily in their organization, coordination, and conditions of activation. This continuity reframes instruction as a process of building students with ideas rather than working against them. Instructionally, a resources-oriented approach encourages instructors to elicit students' reasoning, attend carefully to the meaning students are making, and design learning environments that refine and recontextualize productive resources toward canonical physics understanding. By adopting this framework, the present study aligns prior resources-based research on mechanical waves (Goodhew et al., 2019), obviously committing to an analysis of student reasoning that foregrounds sensibility, context dependence, and instructional leverage. In doing so, this study extends resources-oriented analysis into the domain of EMW and also examines how conceptual resources function in contexts requiring coordination across multiple ontological and explanatory frameworks, including fields, media interactions, and wave-particle descriptions. The abstract nature of EMW provides an opportunity to refine resources-oriented accounts of physics reasoning beyond the primarily mechanical-wave contexts examined in prior work.

Resources-Oriented Research on Electromagnetic Waves

Although much of the literature on EMW has traditionally emphasized misconceptions and instructional deficits, more physics education research has begun to examine students' reasoning about EM phenomena through a resources-oriented lens. This work builds on the premise that understanding EMW requires students to coordinate multiple abstract ideas, oscillating electric and magnetic fields, propagation in vacuum, superposition, polarization, and boundary interactions which are not readily grounded in everyday experience. Early resources-oriented research demonstrated that students can productively draw on prior knowledge and analogies when reasoning about EMW. For example, Podolefsky and Finkelstein (2007) showed that carefully designed analogical scaffolding helps students to activate and reorganize existing conceptual resources, rather than replace incorrect ideas, when learning about EMW propagation. Such studies marked an important shift away from viewing EMW difficulties solely as misconceptions and toward analyzing how students construct meaning in response to instructional contexts.

Following research has extended this perspective by closely examining how students' reasoning about specific EMW phenomena varies across contexts. Studies on boundary conditions, polarization, interference, and diffraction of light reveal that students' ideas are highly sensitive to representations, task framing, and physical scenarios. For instance, Ryan et al. (2018) analyzed student reasoning about EMW at material interfaces and found that difficulties often arise from challenges in coordinating multiple resources, such as field continuity, phase relationships, and boundary limitations, rather than from single, stable incorrect beliefs. Similarly, a series of studies have documented how students reason about polarization and wave optics by activating context-dependent resources related to orientation, oscillation, and energy distribution (Cvenić et al., 2021, 2023; Planinić et al., 2024).

Rather than attempting to eliminate misconceptions, studies suggest that instruction can be designed to elicit, refine, and recontextualize productive resources that students already possess, such as reasoning about oscillation, interaction, or energy flow toward more formal EMW models. Research in engineering and inquiry-based contexts further supports this view, showing that students draw on discipline-specific and experiential resources when reasoning about EMW in communication technologies and wave generation (Gray, 2021; Temes, 2021; Tretter, 2014).

The Physics of Electromagnetic Wave Propagation

EMW are self-propagating disturbances of electric and magnetic fields that travel through space, including vacuum, without requiring a material medium. In classical electrodynamics, EMW arise as solutions to Maxwell's equations, which explain how time-varying electric fields generate magnetic fields and vice versa (Griffiths, 2017; Jackson, 2021). These coupled field variations enable the propagation of EM energy through space at a well-defined speed. In vacuum, this speed is given by $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$, where $\varepsilon_0$is the permittivity of free space and μ_0 is the permeability of free space. Unlike mechanical waves, whose propagation depends on properties of a material medium such as tension or mass density, the propagation speed of EMW in vacuum is determined by fundamental constants.

An EMW can be described as a transverse wave in which the electric field $\vec{E}$ and magnetic field $\vec{B}$oscillate perpendicular to each other and to the direction of the travel. For a plane wave traveling in the x-direction, the fields may be expressed as; $\mathbf{E}(x,t) = E_0 \sin(kx - \omega t)\, \hat{y}, \mathbf{B}(x,t) = B_0 \sin(kx - \omega t)\, \hat{z}$, where $k$is the wave number, ω is the angular frequency, and the magnitudes of the fields are related by $B_0 = E_0/c$ in vacuum (Griffiths, 2017). The wavelength λ, frequency f, and propagation speed v are related by the familiar expression $v = \lambda f$. In a given medium, the speed of propagation may differ from c, depending on the medium's EM properties (permittivity and permeability), but the frequency of the wave is determined by the source and remains unaffected as the wave enters a new medium.

EMW transport energy and momentum through space. The energy density associated with an EMW is distributed between the electric and magnetic fields and, in vacuum, is given by $u = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0} B^2$.

For a plane wave in vacuum, the electric and magnetic contributions to the energy density are equal. The rate at which energy flows through space is described by the Poynting vector, $\mathbf{S} = \frac{1}{\mu_0} x \frac{\vec{E}}{\vec{B}}$, which points in the direction of wave propagation and has magnitude proportional to the intensity of the wave (Griffiths, 2017; Jackson, 2021). These relationships formalize the idea that EMW carry energy without transporting matter, a feature that differentiates EMW from many students' everyday experiences with physical motion.

In material media, EMW motion involves interactions between the fields and charged particles within the medium. These interactions can modify the wave's speed, wavelength, and direction, leading to phenomena such as refraction, reflection, absorption, and dispersion (Born & Wolf, 2013). From a microscopic perspective, the oscillating electric field of an EMW drives charges in the medium, and the collective response of these charges gives rise to the observed macroscopic behavior of the wave. From a macroscopic perspective, these effects are taken by effective material parameters such as refractive index. In both cases, the wave's propagation can still be understood as the transmission of oscillating fields and energy through space, rather than the motion of a material substance.

This physical description shows several features of EMW propagation that are central to student sense-making: the absence of a material medium, the role of oscillating fields, the relationship between frequency, wavelength, and speed, and the transport of energy through space. These features also distinguish EMW from mechanical waves in ways that can shape how students reason about them.

METHODS

Sample

The participants of this study were 37 students (21 female, 16 male) form 12th grade enrolled at the Nazarbayev Intellectual School of Physics and Mathematics located in the Karatau District of Shymkent, operating under the Autonomous Educational Organization "Nazarbayev Intellectual Schools." The physics curriculum for grade 11 and grade 12 at this institution is delivered entirely in English, and students receive six hours of physics instruction per week. Physics is offered as an elective subject and is taught in depth, in alignment with curricula used in many European countries. The school undergoes international CIS accreditation every five years, ensuring consistency with international educational standards.

The instructional unit examined in this study, EMWs, is taught during the first academic quarter of grade 12 and is planned to span six weeks. This duration is substantially longer than that allocated in general secondary schools in Kazakhstan, where the same topic is typically covered in only 4-6 instructional hours. The unit is closely integrated with mathematics and computer science and emphasizes applications in radio electronics, communication and telecommunications, information technologies, and programming.

Instrument

Data were collected using a researchers developed open-ended assessment designed to evaluate students' conceptual understanding of EMWs. The instrument consisted of five open-response questions aligned with the EMWs unit taught in the 12th grade physics curriculum. The questions were constructed to elicit students' scientific reasoning rather than rote recall and to capture both conceptual knowledge and explanatory depth.

The first two questions focused on students' understanding of wave propagation and speed. Specifically, students were asked to reason about the speed of light when transitioning between media (air and water) and to compare the propagation speeds of different EMW (microwaves and visible light) traveling through air. These items targeted foundational concepts related to wave speed, medium dependence, and the invariance of EMW velocity in a given medium. The remaining three questions addressed more advanced conceptual domains. Students were asked to explain how EMW are generated and what mechanisms allow them to propagate through space or matter, to describe how EMW transfer energy in the context of a microwave oven, and to explain whether and why EMW can propagate through a vacuum.

All questions required written explanations and justifications, allowing for the identification of students' conceptual models, alternative conceptions, and levels of scientific coherence.

Initially, seven open-ended questions were developed to assess students' reasoning about EMWs across multiple conceptual contexts. These questions were reviewed by two subject-matter experts in physics education, and revisions were made based on their feedback to improve clarity, conceptual focus, and alignment with instructional goals. As a result of this expert review process, the instrument was refined and reduced to five questions (see **Appendix A**). Prior to administration, the revised instrument was pilot tested with two students to evaluate question clarity, wording, and the appropriateness of the expected response length. No adjustments were made to the questions after pilot testing.

Data Collection and Data Analysis

Data were collected after students had completed the EMW instructional unit. The assessment was administered in paper-based format, and students completed the task individually under regular classroom conditions. Students were given approximately 20 minutes to respond to the questions. The data were analyzed using a resources-oriented qualitative approach, which conceptualizes student reasoning as composed of context-sensitive conceptual resources rather than stable misconceptions. Students' written responses to the five open-ended questions were first organized into analyzable units, defined as one student response to one question.

An inductive open-coding process was used to identify idea-level patterns grounded in students' written explanations. During the initial stage of analysis, both researchers independently reviewed and coded a subset of responses to generate preliminary descriptive codes reflecting recurring forms of reasoning, explanatory structures, and conceptual language. Interrater agreement procedures focused on collaborative comparison of independently generated codes and discussion of differences in interpretation. Interrater reliability was assessed using Cohen's kappa (κ = .89). The researchers then compared and discussed the preliminary codes, resolving coding disagreements through consensus discussion and refinement of code definitions rather than majority assignment. This iterative process resulted in the development of a shared coding framework.

In the second stage of analysis, the preliminary codes were iteratively grouped into broader conceptual resources based on conceptual similarity, explanatory function, and continuity with canonical EM theory. Throughout the analysis process, the researchers repeatedly compared emerging categories across different question contexts and original student responses in order to refine category boundaries and preserve the contextual nature of students' reasoning. The coding framework was revised iteratively until stable resource categories emerged and no substantially new conceptual categories were identified in later stages of analysis. The final framework consisted of seven conceptual resources (R1-R7).

After the coding framework was stabilized, all responses were re-coded using the finalized resource categories. Multiple resources could be assigned to a single response when appropriate. Ambiguous cases and remaining disagreements were revisited jointly by the researchers until interpretive consensus was reached. Consistent with qualitative resources-oriented research, the analysis prioritized interpretive agreement, conceptual coherence, and contextual sensitivity rather than relying exclusively on statistical measures of interrater reliability.

To support trustworthiness and analytic transparency, representative student excerpts were retained throughout the analysis process and used to validate the interpretive consistency of each resource category across contexts. The researchers also engaged in ongoing comparison between the emerging resource categories and the original student responses to minimize overgeneralization and preserve the contextual specificity of students' reasoning.

Following identification of the seven conceptual resources, a descriptive frequency analysis was conducted in which the fraction of students activating each resource was calculated for each question context. A student was counted as activating a resource if that resource appeared at least once in the student's response to a given question. The analysis focused on patterns of resource activation rather than correctness or inferential comparisons. The resulting resource categories were intentionally defined at a mesoscopic level of granularity, capturing recurring patterns of coordinated reasoning across student responses rather than highly atomistic phenomenological primitives. This operationalization was adopted to allow comparison of resource activation across different EMW contexts while remaining consistent with prior resources-oriented PER studies examining broader conceptual reasoning patterns.

RESULTS

The results are organized to show the types of conceptual resources students used, how these resources changed across question contexts, and the frequency with which common resources appeared. We first describe each of the seven conceptual resources found (R1, R2, ..., R7) with representative student excerpts. We then examined patterns of context-dependent resource activation using descriptive frequency analyses across questions.

R1. Medium Interaction Reasoning in Electromagnetic Waves

Students frequently reasoned about EMW behavior by invoking interactions between the wave and the material medium, especially when explaining changes in wave speed as light passes from air into water. In these responses, students attributed differences in propagation speed to properties such as density, molecular composition, or optical characteristics of the medium.

This resource was most strongly activated in responses to question 1, which clearly foregrounded a change of medium. Many students explained slower propagation in water by referring to greater molecular density or increased interaction with particles. For example, one student stated, *"There are more molecules upon which photons will collide in water than air"* (S01, Q1), while another explained that light slows because *"water had denser density, which mean light have to pass through more molecule in water"* (S25, Q1).

Some students articulated this resource using more formal EM language, connecting reduced speed to the medium's EM response. For instance, one student wrote, *"The electromagnetic field of the light wave polarizes the water molecules. The medium responds with a slight delay. Because of this delay, the resulting wave propagates more slowly"* (S26, Q1). Another student similarly noted that light slows due to *"continuous electric polarization re-emissions of light by water"* (S33, Q1).

Even students' explanations sometimes relied on basic mechanistic imagery, such as photons colliding with molecules, this reasoning is continuous with canonical EM theory, which predicts reduced phase velocity in matter due to polarization and interaction with bound charges. Thus, the medium-interaction resource is productive, even when expressed in non-canonical terms.

R2. Constancy of Electromagnetic Wave and Speed Reasoning

A second prominent resource observed in students' responses was reasoning based on the constancy of EMW speed within a given medium. When students compared microwaves and visible light traveling through air, many argued that both waves propagate at the same speed because they are members of the same class of phenomena, that is, EMWs.

This resource was most strongly activated in responses to question 2, which explicitly asked students to compare the speeds of two different EMWs. For example, one student stated, *"Both microwaves and visible light propagate at the same speed in air. This is because they are both electromagnetic waves"* (S22, Q2). Similarly, another student explained, *"Both of them are electromagnetic waves, and in the same medium all electromagnetic waves travel at the same speed"* (S27, Q2).

The constancy-of-speed resource is highly productive, as it aligns closely with canonical EM theory, according to which all EMW travel at the same speed in vacuum and approximately the same speed in air. Several students clearly distinguished speed from frequency and wavelength, noting that while these properties differ, propagation speed does not. For instance, one student wrote, *"What makes them different is their wavelength and frequency … but the speed is the same"* (S25, Q2).

However, this resource sometimes applied too broadly. In a smaller number of responses, students extended the constancy-of-speed idea across different media, saying that light always travels at the same speed regardless of material. As one student wrote, *"The speed of light is constant. Only direction will change"* (S9, Q1). In such cases, a productive idea was used outside its appropriate domain, leading to incomplete or conclusions that require further contextual constraint.

R3. Frequency, Wavelength, and Energy Coupling Reasoning

A third recurring resource in students' explanations involved linking EMW speed to frequency, wavelength, or energy. When reasoning about differences between microwaves and visible light, many students drew on familiar relationships among wave properties, often treating these relationships as determinants of propagation speed.

This resource was also most strongly activated in responses to question 2. For example, one student argued that microwaves travel faster *"because it has longer wavelength"* (S01, Q2), while another explained, *"Visible light because it has higher frequency"* (S06, Q2). Similarly, a student stated, *"Visible light because it has shorter wavelength"* (S18, Q2), clearly linking wavelength to speed.

In several cases, students connect energy to propagation speed, suggesting that higher-energy waves move faster. One student wrote, *"Microwave is faster because it has more energy"* (S17, Q2), while another reasoned that *"waves with a smaller wavelength have a higher frequency, which leads to greater energy"* and therefore faster energy transfer (S37, Q4). These responses show that students are productively drawing on well-known relationships among frequency, wavelength, and energy, even when those relationships are applied beyond their appropriate scope.

The frequency, wavelength, and energy coupling resource is partially productive. It reflects correct distinctions among different types of EMW and recognizes that frequency, wavelength, and energy are related physical quantities. However, difficulties arise when students overgeneralize these relationships, treating frequency or energy as causes of changes in propagation speed within the same medium. For instance, one student said, *"Microwave travels faster than visible light because it has greater wavelength"* (S10, Q2), despite also acknowledging that both waves move through air.

Notably, this resource often appeared alongside the constancy of speed resource (resource 2), sometimes within the same student's set of responses. In such cases, students demonstrated awareness that EMW share a common speed, while simultaneously attempting to reconcile that idea with differences in frequency or wavelength. This pattern suggests that students are actively coordinating multiple resources, rather than replacing one idea with another.

R4. Accelerating Charge and Field Oscillation Reasoning

A dominant resource in students' explanations concerned the idea that EMW are generated by accelerating charges and propagate through mutually oscillating electric and magnetic fields. This resource reflects students' attempts to reason about EMW using field based mechanisms rather than material media.

This resource was most strongly activated in answers to question 3, which clearly asked how EMW are created and how they propagate. Many students correctly identified accelerating charges as the source of EM radiation. For example, one student wrote, *"Electromagnetic waves are produced by accelerating electric charges"* (S10, Q3), while another stated, *"An electromagnetic wave appears when a charge accelerates, or when an electric current changes with time"* (S26, Q3).

Several students expanded this idea by describing the mutual generation of electric and magnetic fields, often invoking language consistent with Maxwell's equations. For instance, one student explained, *"A changing electric field creates a magnetic field, and a changing magnetic field creates an electric field. Because of this mutual generation, the wave can propagate on its own"* (S26, Q3). Similarly, another student wrote, *"The moving charge creates an alternating electric field, which in turn creates an alternating magnetic field. These two fields support each other and travel through space as waves"* (S34, Q3).

Sometimes, students showed this resource using concrete physical systems, such as circuits or antennas. One student described wave creation by noting, *"If we change charges in two wires connected to an LC circuit, these changes make frequency of wave. This way we created electromagnetic wave"* (S30, Q3). Such examples show that students are trying to connect abstract field concepts to familiar physical devices.

The accelerating charge and field oscillation resource is highly productive and, in many responses, closely approximates canonical EM theory. However, the level of mechanistic detail changed substantially. Some students provided detailed, coherent explanations, while others offered abbreviated or partially articulated accounts. For example, one student simply stated, *"Because of the E & M fields oscillating"* (S16, Q3), catching the core idea without elaboration.

R5. Wave Particle Blending Reasoning

Another recurring resource in students' explanations involved blending wave based and particle-based descriptions of EMWs. In these responses, students alternated between, or simultaneously used, language associated with waves (fields and oscillations) and particles (photons, electrons, and collisions) when explaining EM phenomena.

This resource appeared across multiple questions but was most visible in explanations of wave speed in media (Q1) and wave creation and propagation (Q3). For example, one student explained the reduced speed of light in water by stating, *"There are more molecules upon which photons will collide in water than air"* (S01, Q1), framing light explicitly as a stream of particles interacting mechanically with matter. Similarly, another student wrote, *"Light is particles … photons will lose their speed as another object when they collide"* (S23, Q1).

In other cases, students combined particle language with field-based explanations. One student described EMW as *"particles of an electron"* and then added that *"magnetism creates electricity, and electricity creates* *magnetism"* (S29, Q3), blending particle ontology with the idea of jointly generating fields. Another student similarly stated that EMWs consist of *"packages of energy … particles like electron"* that cause heating by vibrating electrons in food (S30, Q4).

The wave particle blending resource is partly productive. On one hand, it reflects students' awareness that EM radiation exhibits both wavelike and particle-like characteristics, a central feature of modern physics. On the other hand, students often lack clear criteria for when each description is appropriate, leading to explanations in which particle-based mechanisms (e.g., collisions and slowing down due to obstacles) are applied to phenomena more accurately described by field interactions.

Especially, this resource often appeared in combination with other resources, such as medium interaction reasoning (resource 1) or accelerating charge reasoning (resource 4). This co-occurrence shows that students are not confused in a global sense but are actively trying to coordinate multiple explanatory frameworks. Difficulties arise when these frameworks are not clearly distinguished or suitably constrained by context.

R6. Self-Propagation in Vacuum Reasoning

A further recurring resource in students' explanations was reasoning that EMW can propagate through empty space without needing a material medium. In these responses, students stated that EMW differ fundamentally from mechanical waves and are instead sustained by electric and magnetic fields that generate one another.

This resource was most strongly activated in responses to question 5, which clearly asked whether EMW can travel through a vacuum. Many students answered agreeably and justified their reasoning by appealing to the self-sustaining nature of EM fields. For example, one student explained, *"They are made of electric and magnetic fields that can exist and move through space by themselves"* (S27, Q5). Another student similarly noted, *"Electric and magnetic fields induce each other and propagate in free space on their own"* (S22, Q5).

Several students supported this reasoning by pointing out astronomical or everyday examples, such as sunlight or radio communication. One student wrote, *"Otherwise, light from the Sun would not reach the Earth"* (S26, Q5), while another argued, *"If not, how we use radio and internet?"* (S07, Q5). These examples indicate that students are drawing on familiar empirical evidence to support the idea of vacuum propagation.

The self-propagation in vacuum resource is highly productive, as it aligns closely with canonical EM theory, according to which EMW consist of oscillating electric and magnetic fields that do not require matter to move. Many students clearly contrasted EMW with sound or mechanical waves, reinforcing this distinction.

However, in some answers, this resource was expressed without a clear mechanistic explanation or was supplemented with slightly related ideas. For instance, one student associated vacuum propagation with earth's magnetic field and cosmic radiation without clarifying the underlying mechanism (S28, Q5). Sometimes, students stressed that EMWs require "particles" even in vacuum, indicating partial coordination with wave particle reasoning.

R7. Energy Transfer to Matter Reasoning

A final prominent resource in students' reasoning concerned how EMW transfer energy to matter, especially in the context of microwave heating. In these responses, students focused on the interaction between EM fields and material particles, most commonly water molecules in food, to explain how energy carried by waves is changed to thermal energy.

This resource was most strongly activated in responses to question 4, which explicitly asked students to explain how a microwave oven heats food. Many students described heating in terms of molecular motion, stressing vibration, rotation, or collisions. For example, one student explained, *"The waves vibrate water molecules in the food"* (S11, Q4), while another stated, *"Microwaves heat food by changing kinetic energy of molecules"* (S13, Q4).

Several students provided more detailed mechanistic explanations that closely resemble canonical descriptions of dielectric heating. One student wrote, *"Water molecules begin to oscillate and rotate under the influence of the electric field … the internal energy increases, that is, the food heats up"* (S22, Q4). Another student similarly explained that *"the electric field forces water molecules to continuously rotate back and forth … collisions convert the energy of the electromagnetic field into heat"* (S26, Q4).

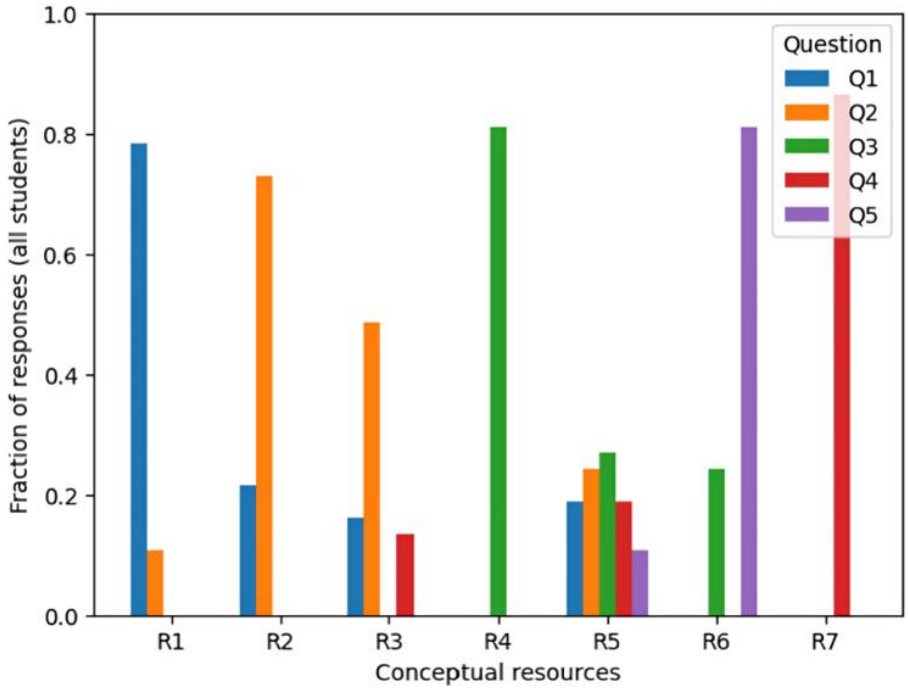

Figure 1. Fraction of responses using each of the seven common conceptual resources for five questions (generated by the authors)

Sometimes, students expressed this resource in more general terms, stating simply that EMWs "carry energy" that is then transformed into heat. For instance, one student wrote, *"EM waves transfer energy … the wave will generate heat in the food"* (S01, Q4), while another noted, *"Waves with smaller wavelength have higher energy … this energy is transferred to the food"* (S37, Q4). These responses indicate recognition of energy transport, even when the conversion mechanism is not fully expressed.

The energy transfer to matter resource is highly productive, as it reflects a correct understanding that EMW can deliver energy to material systems and increase their internal energy. However, the resource is sometimes partial, mainly when students conflate energy transport with particle collisions or when they neglect the role of the oscillating electric field in driving molecular motion.

Frequency of Common Conceptual Resources

To address **RQ2** and **RQ3**, we examined how the identified conceptual resources varied across different EMW contexts and which resources appeared most prominently or only marginally within each question context. We analyzed the frequency with which each common resource (R1-R7) appeared in students' responses to each question. Following a resources-oriented approach, this analysis focuses on patterns of activation, rather than correctness or internal coherence, and treats resources as context dependent ideas that may be activated differently by different prompts.

For each question, we calculated the fraction of student responses using each resource, disaggregated by students. A student was counted as using a given resource if that resource appeared at least once in the student's response to the relevant question. **Figure 1** shows the fraction of responses using each of the seven common conceptual resources for five questions.

Figure 1 shows the fraction of responses using each conceptual resource (R1-R7) across all five questions for the full student sample (n = 37). Each set of bars represents a different question, revealing distinct resource activation profiles for different contexts. Medium-interaction reasoning (R1) is most prominent in question 1, constancy-of-speed reasoning (R2) in question 2, accelerating-charge and field-oscillation reasoning (R4) in question 3, energy-transfer reasoning (R7) in question 4, and vacuum-propagation reasoning (R6) in question 5. The minimal overlap of dominant resources across questions shows the strong context dependence of students' reasoning about EMWs.

DISCUSSION

This study identified seven common conceptual resources that students activated when reasoning about EMW across five distinct question contexts. The results show that students' reasoning is context dependent, and also that students coordinate qualitatively different types of conceptual resources depending on whether the context foregrounds media interactions, field oscillations, energy transfer, or wave-particle explanations.

The conceptual resources identified in this study are defined at a broader level of granularity than the fine-grained phenomenological primitives originally emphasized in early resources theory. Rather than isolating microscopic knowledge elements, the present analysis focuses on recurring patterns of coordinated reasoning that students used productively across EM contexts. This mesoscopic operationalization aligns with prior resources-oriented research in physics education that has examined broader clusters of coordinated reasoning, rather than exclusively fine-grained phenomenological primitives, in order to investigate context-dependent activation and coordination of ideas during scientific reasoning (Goodhew et al., 2019; Hammer, 2000).

The findings show that students' reasoning about EMWs is not well characterized by stable misconceptions alone. Many students activated canonically productive ideas in some contexts while overgeneralizing or inconsistently coordinating those same ideas in others. From a resources-oriented perspective, this pattern suggests that conceptual difficulty in EMW may arise less from the absence of scientific knowledge and more from challenges in coordinating multiple productive resources across contexts involving fields, media interactions, energy transfer, and wave-particle descriptions.

Some responses were particularly difficult to classify within a single resource category because students shifted dynamically between wave-based and particle-based explanations. For example, one student explained that light slows in water because "photons will lose their speed" through collisions with atoms, but then immediately contrasted this with a wave-based explanation in which "it changed only wavelengths" (student 23). Another student described EMWs as "particles of an electron" while simultaneously explaining propagation through mutually generating electric and magnetic fields (student 29). Rather than reflecting globally incoherent thinking, these responses suggest active attempts to coordinate multiple explanatory frameworks that were only partially stabilized.

Several responses further showed that students were not simply activating isolated resources independently but were attempting to coordinate partially compatible ideas within the same explanation. For example, one student stated that "both are EMWs, so they will have the same speed in one surrounding" while elsewhere explaining that photons "lose their speed" through collisions with atoms in denser media (student 23). Similarly, another student correctly noted that EMWs "do not require a medium" while also arguing that microwaves travel faster because they have a longer wavelength (student 1). From a resources-oriented perspective, such tensions may reflect difficulties in constraining and coordinating multiple productive ideas appropriately across contexts rather than the presence of a single stable misconception.

Consistent with a resources-oriented perspective, the frequency patterns, presented in **Figure 1**, support the view that students possess a repertoire of productive conceptual resources that are activated selectively rather than applied uniformly. The absence of many resources in particular contexts should not be interpreted as a lack of understanding, but rather as evidence that students draw on ideas they perceive as most relevant to the situation at hand. This analysis thus provides views about how students organize their reasoning about EMW and shows the instructional importance of eliciting and coordinating, rather than replacing, students' existing ideas.

The findings of this study both align with and extend prior research on students' understanding of waves and EM phenomena. Consistent with earlier studies, students' reasoning was found to be strongly context dependent, with different conceptual ideas activated by different question framings. Research on mechanical waves and sound has long documented that students do not apply a single, stable conception across contexts, but instead draw selectively on ideas related to surface features and task demands (e.g., Tongchai et al., 2009; Wittmann, 2002; Xie et al., 2021). Our results demonstrate that this pattern of context dependence was observed in EMW contexts, including abstract contexts such as field-based wave generation and vacuum propagation.

Several specific resource patterns observed in this study mirror well-documented findings in the literature. For example, the prominence of medium interaction reasoning when students compared wave speeds in air and water is consistent with prior work showing that students often attribute changes in wave behavior to properties of the medium (Saglam & Millar, 2006; Wittmann et al., 2003). Importantly, rather than treating this reasoning as a misconception, our resources-oriented analysis shows its productive potential in contexts where material interactions are physically relevant, reflecting calls in the literature to move beyond deficit-based interpretations of student thinking.

At the same time, the dominance of constancy of EMW speed reasoning when students compared microwaves and visible light in air contrasts with earlier reports that students frequently conflate speed, frequency, and energy for EMW (Kotsis, 2024; Salele et al., 2025). Our findings show that, under appropriate framing, many students can activate a canonically aligned idea about speed constancy, indicating that previously reported difficulties may reflect challenges in resource coordination rather than a lack of relevant knowledge.

The strong activation of accelerating charge and field oscillation reasoning in explanations of EMW generation further extends prior work. Earlier studies emphasized students' difficulties with field concepts and Maxwellian descriptions of EM phenomena (Maloney et al., 2001). In contrast, our results show that many students readily invoke field-based mechanisms when the task explicitly calls for them, supporting a resources-oriented view in which such ideas are present but not uniformly activated.

Similarly, the dominance of energy transfer to matter reasoning in explanations of microwave heating aligns with research showing that students more readily reason about EMW in applied or everyday contexts (Podolefsky & Finkelstein, 2007; Tretter, 2014). Our analysis clarifies that this energy-based reasoning is not merely intuitive but represents a coherent conceptual resource that can serve as a bridge to more formal descriptions of EM energy flow.

Finally, the strong activation of self-propagation in vacuum reasoning contrasts with earlier studies that reported widespread student resistance to the idea that waves can propagate without a medium (Viennot & Rainson, 1992). While some students in our study provided limited mechanistic detail, the frequency results indicate that the core idea itself is robust, suggesting that instructional challenges may lie more in deepening explanations than in introducing the concept.

CONCLUSIONS, LIMITATIONS, AND IMPLICATIONS

This study investigated students' reasoning about EMW using a resources-oriented perspective across five conceptual contexts. Analysis of students' written responses revealed seven common conceptual resources that were activated in strongly context-dependent ways. Rather than applying a single, stable conception of EMW, students selectively drew on different ideas depending on the nature of the question, such as wave speed, wave generation, energy transfer, or propagation in vacuum.

The findings additionally show that reasoning about EMW involves a distinctive form of resource coordination not commonly emphasized in earlier resources-oriented studies of mechanical waves. Students frequently moved between field-based, medium-based, and particle-based explanations depending on contextual cues, indicating that conceptual understanding in EMW may depend heavily on the coordination of multiple explanatory frameworks rather than the replacement of incorrect conceptions.

Across contexts, distinct resources consistently dominated: medium interaction reasoning for wave speed in materials, constancy of speed reasoning for comparisons among EMW types, accelerating charge and field oscillation reasoning for wave generation, energy transfer reasoning for microwave heating, and self-propagation in vacuum reasoning for propagation without a medium. These patterns were stable across the student sample and indicate that students possess a repertoire of productive conceptual ideas that are activated selectively rather than uniformly.

Although the present study identified recurring patterns of resource activation across contexts, the written-response format limited detailed examination of how students dynamically transition between and reconcile competing conceptual resources during real-time reasoning. Several responses revealed ambiguity, instability, and partial coordination among multiple explanatory frameworks, indicating that future interview-based and discourse-oriented studies could provide richer insight into the moment-to-moment organization of students' reasoning about EM phenomena.

The results have several implications for teaching and learning about EMW. First, instruction should clearly address the context dependence of reasoning, helping students recognize when particular ideas are productive and when they require refinement. For example, medium based reasoning can be leveraged productively in discussions of refraction and dispersion, while being carefully contrasted with field-based explanations of propagation in vacuum. Second, the presence of canonically aligned resources such as constancy of speed reasoning and vacuum propagation reasoning proposes that instruction can build on existing student ideas rather than introducing concepts as entirely new. Activities that prompt students to compare and coordinate multiple resources across contexts may support deeper conceptual understanding. Third, applied contexts such as microwave heating appear to strongly elicit energy-based reasoning. Instruction can use these contexts as bridges to more formal representations, such as field descriptions and energy flow, rather than treating them as separate from main EM theory.

Future research could extend this work in several directions. Interview based studies could provide richer views about how students coordinate multiple resources in real time and how their reasoning shifts during discussion or instruction. Additional research could also explore how these conceptual resources vary across different educational levels, instructional approaches, or cultural contexts. Finally, applying a similar resources-oriented analysis to other topics in electromagnetism such as induction, radiation, or EM energy flow could further clarify how students reason across the broader EM domain.

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Ethics declaration: This study was approved by the Institutional Review Board at South Kazakhstan Pedagogical University named after O. Zhanibekov on 15 October 2025 with approval number 16. Prior to data collection, all necessary institutional permissions were obtained, and the study was conducted in accordance with ethical guidelines for educational research. Students were informed about the purpose of the study, the voluntary nature of their participation, and their right to withdraw at any time without any academic consequences. Informed consent was obtained from all participating students. To ensure confidentiality and anonymity, no personal identifiable information was collected. Student responses were coded using numerical identifiers, and all data were reported in aggregate form only. The paper-based responses were converted into digital format, and the digital data were stored securely and accessed solely by the researchers for analysis purposes.

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APPENDIX A

Question 1:

Suppose a beam of light passes from air into water. Will the speed of light in water be greater than, less than, or the same as in air? Explain why you think so.

Question 2:

A microwave and a visible light wave travel through air. Which one travels faster? Why? Explain your reasoning.

Question 3:

How is an electromagnetic wave created? Describe what causes it to propagate through space or a material. Please explain in detail.

Question 4:

A microwave oven heats food using electromagnetic waves. Explain how these waves can transfer energy to the food. What happens during this process?

Question 5:

Can electromagnetic waves travel through empty space (a vacuum)? Why or why not? Describe what allows or prevents their propagation.