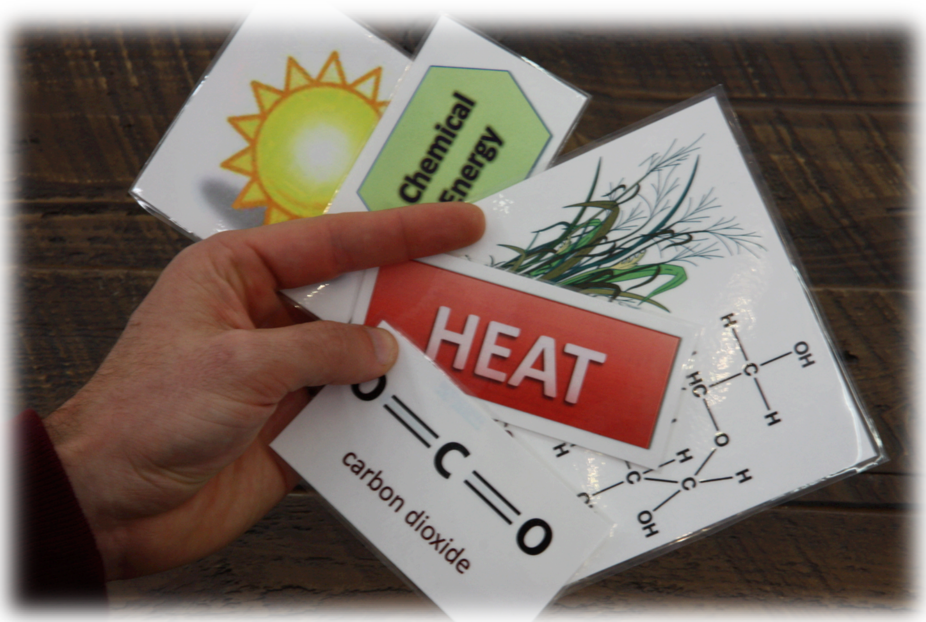
What learning progressions tell us about students' ability to participate in the global climate change and biofuels debates



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Abstract

Our society is currently having serious debates about sources of energy and global climate change. But do students (and the public) have the requisite knowledge to engage these issues as informed citizenry? The learning progressions research summarized here indicates that only 10% of high school students typically have a level of understanding commensurate with that called for in *The Next Generation Science Standards*. The learning progression research shows how most students fall short of being able to trace matter and energy through carbon-transforming processes such as photosynthesis, respiration, and combustions that are at the center of analyses of our usage of different energy sources and global climate change. We discuss the more typical types of understanding that students develop and their implications for teaching.

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Introduction

Matter and energy changes in biological carbon-transforming processes such as photosynthesis, cellular respiration, and combustion are at the heart of serious issues currently facing our society – energy sources and global climate change. Do students (and the public) have the requisite knowledge to engage these issues as informed citizenry?

Learning progressions and the Next Generation Science Standards

In order to follow the public discussion of these issues, people need the type of understanding targeted by the *Next Generation Science Standards* (NGSS, NRC 2013) and *The Framework for K12 Science Education* (NRC, 2012). The *Framework* describes crosscutting concepts that are meant to complement scientific practices as organizational tools that learners can use to develop and check their growing understanding. Of the seven crosscutting concepts listed, tracing matter and energy is the one that applies most directly to the issues of energy sources and global climate change. The implication is that by tracing matter and energy, students should be able to connect familiar events such as plants and animals growing, engines running, and organic materials decaying with atomic-molecular processes—chemical changes such as photosynthesis, cellular respiration, and combustion—and with energy flow and carbon cycling at ecosystem and global scales. Figure 1 below represents this type of understanding. In this diagram, matter (represented by green text and arrows) cycles between living things and the atmosphere. Energy (represented by red text and arrows) does not cycle. Sunlight is transformed into chemical energy in biomolecules and eventually in ATP and finally into work and heat which cannot be reused by living organisms.

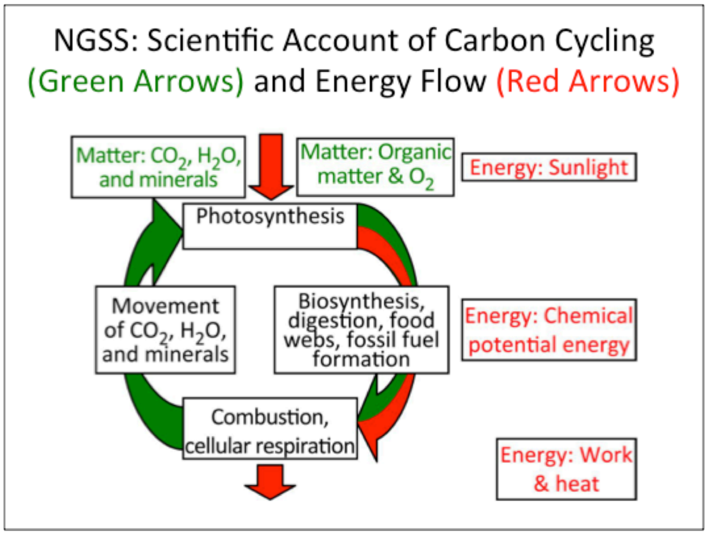

Figure 1: NGSS goals for student understanding

But do students have this type of connected, organized and flexible knowledge? Can they use the conservation rules to check their accounts of matter and energy changes during the processes that affect biofuels, fossil fuels, and atmospheric CO_2 levels? When we talk to *successful* science students, what they have to say is troubling. The following quotes are from college students who were interviewed about matter inputs, outputs, and exchanges among organisms. These students were interviewed after receiving instruction (in an introductory biology course for science majors) and passing a test on the topics of the interview.

Susan: *In photosynthesis, [coming in are] CO_2, starch or glucose. Coming out is oxygen, water, and energy.*

Ruth: *Well I know that the light makes it [radish plants] grow which gives it like, nutrition, which it gets from the dirt and the water. And it takes in the nutrition into the…, photosynthesis also adds to it (sounds unsure). And it gives, I know it gives off CO_2 and that releases off, but it doesn't really add to the weight.*

Mark explaining the fate of the mass lost by someone on a diet: *The fat was converted into useable energy and burned by muscle contraction for movement.*

None of these students appeared to notice that his/her explanation included the creation or destruction of matter. Despite prodding from the interviewer, Susan gave an account of photosynthesis where carbon is a part of all of the inputs, but none of the outputs of photosynthesis. She also failed to identify a source of the energy produced. Similarly Ruth's account of how growing radish seeds gain mass does not identify the source or origins of the increasing mass in the growing plant. Mark's account of how someone on a diet loses weight had matter (fat) being converted into energy.

Compare these quotes to Burt's account of the source of mass of radish seeds growing in light and water: *And then how this increase in mass, bio-mass, [radish seeds in light] occurred would obviously be not from water, so it had to be from something else like some sort of glucose or something like that… It [glucose] is made of* $C_6H_{12}O_6$ *and so it needs the* CO_2 *to make for the carbon and it has water that uses H for the water from the water, too* (Authors, 2012). Although he could not immediately generate an answer, he realized that he needed to account for the each of the elements in the glucose that was produced by photosynthesis. Tracing matter was a tool that he used to generate an explanation.

Why do so many students' accounts differ from the scientific explanations? Are there patterns in how students reason about these familiar carbon-transforming processes? What do the patterns in students' developing ideas tell us that might help us develop more effective instruction?

In this article, we examine the answers to these questions based on the learning progressions research reported in Mohan, Chen, and Anderson (2009) and Jin and Anderson (2012). Learning progressions are "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (*e.g*., six to eight years)" (Duschl, Schweingruber, & Shouse, 2007). Learning progressions are developed by analyzing written responses and interviews of many students in a variety of grades and settings, looking for patterns in their responses, and organizing groups of similar responses by degree of sophistication. Longitudinal studies are used to see if individual students actually progress through the designated levels.

Learning progression research differs from misconceptions research in that it looks at students' ways of approaching a broad set of ideas rather than their understanding of a specific concept. The *Framework for K-12 Science Education* and *NGSS* are informed by learning progression research. The learning progressions reported in this article examine how students learn to use the crosscutting concepts of matter and energy conservation to make sense of carbon-transforming processes.

Methodology

Because we are interested in students' ability to use the conservation laws as schemata for understanding carbon-transforming processes, the learning progression we describe here is based on analysis of interviews of students' and experts' written responses to open-ended questions. The results are based on interviews with 8 elementary, 22 middle school, and 26 high school students and written responses to open-ended questions by 481 elementary, 1001 middle, and 740 high school students (Jin and Anderson, 2009; Mohan, Chen, and Anderson, 2009). Students came from a variety of settings from several states. Tests and interviews included questions about everyday situations so that all students would have something to contribute. We looked for patterns in their responses and organized groups of similar responses by degree of sophistication. Longitudinal studies were used to see if individual students actually progress through the designated levels. We have done parallel work with undergraduates in introductory biology courses using interviews and essay and forced-choice questions (Authors, 2012; Authors, 2006; Aithors, 2011).

How students develop an understanding of matter and energy in carbon-transforming processes– descriptions of learning progression levels of understanding

In our research we have focused on students' accounts (descriptions and explanations) of familiar carbon-transforming processes: plant and animal growth and movement, decay, and combustion of organic materials. We describe our findings in terms of four levels of achievement, from Level 1 (typical of students in upper elementary school) to Level 4 (the integrated understanding described in the *NGSS* and Figure 1, above). The lower levels represent ways of thinking and using language that come to us through our shared cultural heritage; the upper levels successfully use the knowledge and practices of science.

Level 1

Level 1 students are almost exclusively elementary or middle school students. However, their thinking sheds light on the origin of older students' ideas. Figure 2 is quite different from Figure 1. Unlike Level 4 students, Level 1 students do not think about cycles. In order to identify cycles, one has to identify something in common in the components in the cycle. For example, in Figure 1 we are really tracing carbon, hydrogen, and oxygen. But Level 1 students don't see these commonalities. Their accounts focus on what they can see and they interpret events in everyday language. They envision the events of the world as taking place because *actors* such as people, animals, plants, or even flames make them happen. Actors have needs or *enablers* that they must use to fulfill their purposes. Enablers can include materials (*e.g.,* soil minerals for plant growth), energy sources (*e.g.,* sunlight), causes (*e.g.,* the match that starts a fire), or conditions (*e.g.,* warmth or care). For Level 1 students, a good explanation tells how the enablers help the actors to achieve their purposes. They do not see that, "you are what you eat." They think of food as the necessary enabler for life, growth, or energy, but not as substance that becomes part of the eater or has chemical potential energy. Thus materials may appear or disappear or the fate of materials may not be part of the story at all.

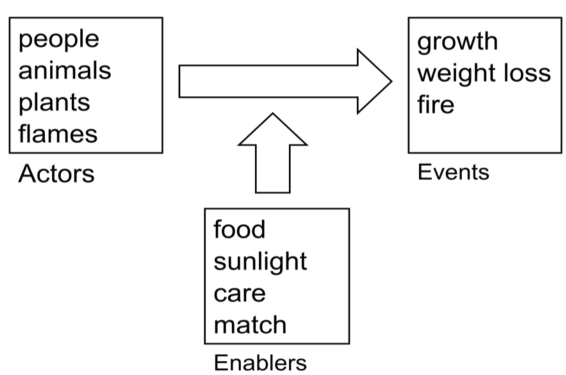

Figure 2. Level 1 understanding

The following quotes (shown in italics) are representative of the accounts of Level 1 students.

Interviewer: *Do you know how the girl's body uses it [food] to grow?*
Watson: *Because the food helps make energy for the girl so then she can like learn how to walk and crawl and stuff. And then it will also help the baby so it will be happy, be not mean and stuff.*
Here the natural process is growth and development, which happens when a child has food. Like most Level 1 students, Watson does not clearly distinguish between growth and other actions that are enabled by food such as learning to walk and crawl or being happy.

In response to a question about where the mass in a large tree comes from, Martran: *I think its leaves. Leaves come from trees; the weight comes from when a plant grows the weight also grows bigger.*
Martran identifies leaves as part of the new mass, but he doesn't trace the matter back to its origins. Like many level 1 students, his explanation for the increased mass is simply that the tree has gotten bigger.

Describing what happens to a match when it burns:
Alicia: *Because as the match burns, the flame moves down the stick and burns the wood until it is gone.*
In this account, the flame consumes the wood and makes it disappear.

Level 2

Level 2 reasoning (Figure 3) is common in students of all ages, from elementary school up to, and including, college science majors. Level 2 students still tell stories about actors and enablers, but they include additional details, which allow them to recognize cycles. In their stories, specific processes have specific needs. The stories often include material inputs and outputs, but the inputs and outputs are restricted to what is visible and a few specific gases. Thus they identify a cycle where oxygen and carbon dioxide are exchanged between plants and animals. Some vague solid matter, often identified as "nutrients", also cycles between organisms. The transformations of inputs to outputs don't follow scientific rules such as conservation of matter. In the examples below, Level 2 students identify soil, fertilizer, sweat, and ash as inputs or outputs. Atoms are not traced and materials may turn into energy. Food or fuel is seen as a physical necessity for some hidden process. Energy may be a ubiquitous enabler or connected with particular substances.

Reaganne: *I think their [the plants'] weight comes from the soil and fertilizer because as it grows it increases in weight and fertilizer and soil are the things that make a plant grow.*

Hadid: *It [the fat] turned into energy and it got burnt and came out through sweat.*

Jenna: *The wood [of the match] burns into ash and it loses weight because it is losing mass.*

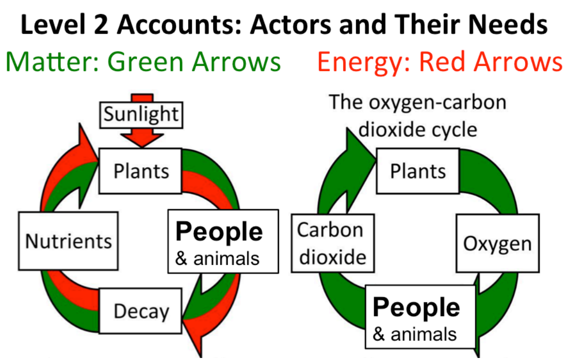

Figure 3. Level 2 Accounts

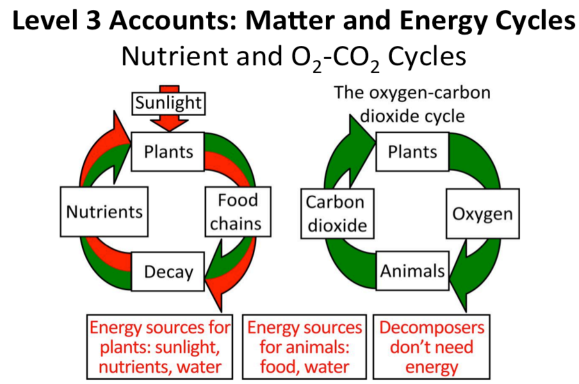

Figure 4. Level 3 Accounts

Level 3

Level 3 students (Figure 4) are mostly high school students (or older). They have a more microscopic view of the world that includes cellular processes such as respiration and photosynthesis, as well as many scientific vocabulary words. They recognize the importance of tracing matter and energy, but are unable to do so successfully. Rather than sequences involving actors and enablers, and they are much better at identifying key subsystems (such as cells, molecules, and atoms), materials (such as glucose and other organic materials, in addition to oxygen, carbon dioxide, and water), and forms of energy. However, they still are not able to trace matter and energy through the scientific carbon cycle, and therefore their cycles are very similar to those of Level 2 students. These students attempt to identify the elements in some inputs and/or outputs. In addition, they add energy into their accounts of the food chain and combustion, but they make mistakes and therefore their accounts of cycles are very similar to those of Level 2 students (Figure 3). For example, energy may cycle with the carbon returning to plants in the nutrients in the soil (*i.e.*, both energy and matter recycle), or energy may get used up and disappear. In general, Level 3 students trace matter and energy intermittently, inconsistently, inaccurately or incompletely. Level 3 students know about the laws of conservation of matter and energy, but they often give accounts that don't follow conservation rules. The quotes below give examples of Level 3 thinking.

Felicia: *The weight [of the plant] comes mostly from H_2O it receives which it uses in its light reactions to eventually produce glucose to provide itself with energy.*
Felicia does not attempt to account for the carbon source of the glucose.

Richard: *The gasoline is burned while it's in the engine. And all the bonds in it are broken and rearranged. And then it goes out the exhaust into the atmosphere as carbon dioxide…*
Interviewer: *So where does the energy initially in the gasoline go?*
Richard: *It runs through the engine and then is converted to carbon dioxide.*
Richard's account traces carbon, but not oxygen and hydrogen. Like many Level 3 accounts, Richard's account includes a matter-energy conversion.

Interviewer: *Okay. So, do you think that the tree needs energy?*
Rachel: *Yeah.*
Interviewer: *Where does the energy come from?*
Rachel: *When it burns the glucose to make its food.*
Interviewer: *So the energy comes from glucose?*
Rachel: *Yeah.*
Interviewer: *Okay. So where does the energy of the glucose come from?*
Rachel: *In its bonds in like carbon to carbon and carbon hydrogen bonds.*
Interviewer: *So where does that energy come from?*
Rachel: *In the bonds of the carbon dioxide and the water.*
Rachel is "almost there;" she successfully traces energy through several processes, but then traces the chemical energy in glucose back to the matter that glucose is made from (carbon dioxide and water) rather than to its energy source (sunlight).

Level 4

Level 4 students have developed a *sense of necessity* with respect to accounts of carbon-transforming processes—a sense that an account is not complete or accurate unless matter is conserved and energy is conserved and degraded in every individual process and in the system as a whole. Thus the conservation rules are used as tools for analyzing processes.

Cheryl: *The plant's increase in weight comes from CO_2 in the air. The carbon in that molecule is used to create glucose, and several polysaccharides, which are used for support.*

Interviewer: *So what does a flame need in order to keep burning?*
Eric: *Flame needs a source of fuel, which has the higher energy bonds like carbon and hydrogen and it also needs oxygen in order to help break that apart.*
Interviewer: *So if you look at the flame. So over time, you know, the wood, part of the wood, as the wood was burning, you know, lost some weight, right? So where does the lost material go?*
Eric: *It is similarly to when something is eaten. It is converted and recombined with the oxygen to be carbon dioxide and water vapor, which is released into the atmosphere around it.*

Thus Cheryl and Eric explain carbon-transforming processes in ways consistent with *NGSS* and scientific accounts. Level 4 students trace matter and energy across scales without confounding the two. Elements (C, H, and O) that are part of inputs are also identified in corresponding outputs. Energy is not always associated with the same atoms. Thus energy is associated with molecules that have reduced forms of carbon and hydrogen (C-C and C-H bonds) rather than oxidized forms (C-O or H-O bonds). The energy in a system is ultimately transformed into low-grade thermal energy that cannot be recycled. Thus, matter cycles and energy flows.

Summary of Learning Progression

We can now see that the three seemingly random responses from the college students quoted in the introduction fit the patterns described by the learning progressions. Susan is a level 3 student who thinks about photosynthesis at the molecular level. She identifies specific molecules as inputs and outputs, but does not feel constrained to account for all of the elements and the source of the energy. Ruth has a level 2 understanding of photosynthesis where gases cycle separately from solids. Mark has a level 2 or 3 understanding of respiration. In his account, he converts matter into energy, which disappears.

The learning progression research shows that only Level 4 students consistently trace matter and energy. This understanding is a significant intellectual accomplishment, requiring students to develop new ways of interpreting familiar phenomena. It requires looking at familiar objects and organisms and seeing them as being made of organic molecules with high energy bonds. It means requiring that explanations of processes account for all atoms and all energy transformations. As shown in Table 1 (from Authors, 2009), students who don't think this way see different patterns in the carbon-transforming processes. The familiar processes that we asked students to explain are on the shaded row in the middle of the table. Lower-level students see the processes involving living plants and animals as all similar—driven by living actors and their enablers. For these learners, decay is quite different—something that happens naturally to dead things, and combustion is also different. Level 4 students, on the other hand, are able to classify the processes according to their underlying chemical changes, so these learners see quite different patterns in what is alike and different. Photosynthesis is unique as a process that creates organic materials out of inorganic matter. Food chains involve multiple transformations in organic matter. Three processes that seem completely different to lower-level learners—animal movement, decay, and combustion—are seen by Level 4 students as all relying on energy released by oxidation of organic matter.

Table 1: Contrasting ways of grouping carbon-transforming processes

Carbon-transforming process	Generating organic carbon	Transforming organic carbon			Oxidizing organic carbon		
Scientific accounts	Photo-synthesis	Biosyn-thesis	Digestion	Biosyn-thesis	Cellular respiration		Combustion
Macroscopic Events	*Plant growth*		*Animal growth*		*Breathing, exercise, weight loss*	*Decay*	*Burning*
Informal accounts	Plants and animals accomplishing their purposes, enabled by food, water, sunlight, air, and/or other resources					Natural process in dead things	Flame consuming fuel

Implications for teaching

What are the implications of these learning progression findings for teaching? The biggest difference between Levels 3 and 4 is a commitment and ability to trace matter and energy. That is, students with a Level 4 understanding use tracing matter and energy as analytical tools or crosscutting concepts (NRC, 2012) for examining processes. Very few students achieve Level 4 understanding of these processes.

Rice *et al.* (in press) have shown that with non-science majors at the college level, when instruction explicitly and consistently uses tracing matter and energy as an organizational framework, more students advance to a Level 4 understanding than in classes that use less directed active learning (42% vs. 16%). Insistence on precise and consistent use of language by both teachers and students appears to be another common factor of the instruction in these effective classrooms. For example, the difference between "the food was used to provide energy" and "the food was converted to energy" is subtle but important.

In the Carbon TIME curriculum, currently being developed for middle school and high school students in a partnership among Michigan State University, the National Geographic Society, and the Seattle Public Schools (http://edr1.educ.msu.edu/environmentallit/publicsite/html/CarbonTIME.html), explicit instruction about how to use the crosscutting concepts of matter and energy takes the form of rules (atoms last forever, atoms can be rearranged to form different molecules, energy lasts forever) and questions that students are routinely asked as they develop models for the processes they explore. The questions are: Where are atoms moving? What is happening to carbon atoms? What is happening to chemical energy?

Implications for understanding current issues related to energy usage and global climate change

We believe that the understanding of carbon cycling depicted as the Level 4 understanding in Figure 1 and included in *NGSS* is essential for our high school graduates to engage as informed citizens in the discussions of global climate change and to make informed and responsible decisions. They will need to connect everyday events, news items, and knowledge of the global carbon cycle using conservation of matter and energy. All the carbon atoms in our environment have to be *somewhere,* and through carbon-transforming processes that happen every day we decide where those carbon atoms will go. The learning progressions research shows that many (~35%, Authors, 2009; Authors, 2012) high school students, and therefore probably much of the public, have a Level 2 understanding of carbon-transforming processes. Many of these people do not connect gas cycles (CO_2 from animals ←→ oxygen from plants) with cycles of nutrients or carbon-containing solids.

Only 10% of high school students typically have a level 4 understanding (Authors, 2009; Authors, 2012). However, even with a level 3 understanding, people will have difficulties understanding the consequences of decisions they make for atmospheric carbon, because they make mistakes tracing matter and energy, losing sight of one or the other in multi-step processes.

For example, when trying to weigh the costs and benefits of biofuels, Level 3 students are likely to have trouble evaluating the advantage of fuels that, like gasoline from petroleum, produce carbon dioxide when they are burned. To understand the argument, they need to trace those carbon atoms further back to their origins in recent photosynthesis or in carbon that was previously sequestered underground.

But the biofuels story is more complex than that. Consider the work of the Great Lakes Bioenergy Center where scientists and engineers investigate multiple biomass crops, agricultural practices, and biofuels preparation processes. Some methods for producing biofuels consume almost as much fuel as they produce. Other methods release more carbon dioxide from the soil than fossil fuels release when they are burned (Searchinger *et al.*, 2009). So we can't just teach students that biofuels are "good" or "bad" for climate change. Instead, we must prepare them to make informed choices about methods for producing biofuels that haven't even been invented yet. Evaluating such scenarios requires a commitment to tracing matter, particularly carbon, without being side-tracked by more or less appealing “green” stories.

Thus learning progression research helps us understand: why students’ accounts of basic processes are garbled, how we can do a better job teaching these using conservation laws as analysis tools and not just additional facts, and why it is difficult for many people to assimilate and evaluate the information surrounding global climate change.

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