Students' progression in understanding matter

	Basic model	Structure and composition	Physical properties and changes	Chemical properties and change	Conservation
5	*Systemic particle concept* Students describe matter and their properties through interactions in a system of particles (Crespo & Pozo, 2004; Gómez et al. 2006; Stevens et al., 2010; Talanquer, 2009).	*Systemic particle concept* Students are able to describe and to explain the structure of complex molecules (Urhahne et al., 2009). They are able to explain why specific interactions in a system of particles occur. (Stevens et al., 2010). *Examples of typical student statements* • Carbon atoms may be present in different hybridizations (Taber, 2005). • Mesomeric structures are used to illustrate the molecule. It is stable through mesomerism (Taber, 2005). • By adding heat electrons spin more and more (Adbo & Taber, 2009).	*Systemic particle concept* Students are able to trace physical properties of matter and conditions for physical changes back to the properties of particle collectives (Johnson, 2005; Johnson & Papageorgiou, 2010; Papageorgiou et al. ,2010; Salta & Tzougraki, 2011). *Examples of typical student statements* • The different properties of diamond and graphite can be traced back to different hybridizations of the carbon atom (Taber, 2005). • Color can be influenced by the size of the conjugated double bond system and emitting electrons (Taber, 2005). • Strength of intermolecular forces is a reason for low melting/boiling points or for the different states of matter (Othman et al., 2008; Treagust et al., 2010). • Electric conductivity is set by negatively charged ions (Calik, 2005).	*Systemic particle concept* Students are able to name factors that help them to explain the behavior of reactions of a substance (e.g. electron configuration) (Adbo & Taber, 2009). They are able to justify possible reaction progresses by taking a variety of influencing factors into account (pressure, temperature, structure of all participating substances in the reaction) (Treagust et al., 2010). *Examples of typical student statements* • A second-order reaction has taken place. • An acid-base-reaction has taken place (Liu & Lesniak, 2006). • This reaction is effected by means of a non-stable transition state. • Equal signs show that the reaction runs in both directions (Kermen & Méheut, 2011).	*Systemic particle concept* Students are able to use energy and matter concepts to describe conservation for example by including laws of thermodynamics in their explanations (Taber, 2005). *Examples of typical student statements* • The inner energy of a closed system is constant. • The mass of the nucleons is smaller than the mass of the atomic nucleus (Stevens et al., 2010).
4	*Differentiated particle concept* Students describe matter as consisting of particles (e.g. atoms), which also consists of further particles (Gómez et al., 2006; Liu & Lesniak, 2005; Liu & Lesniak, 2006; Löfgren & Hellden, 2009; Smothers & Goldston, 2010; Stevens et al., 2010; Talanquer, 2009).	*Differentiated particle concept* Students are able to describe particles with the use of a differentiated atom model (e.g. nucleus-shell, shell model) (Adbo & Taber, 2009). They differentiate between atoms and molecules and can distinguish between different bond types (Gómez et al., 2006; Löfgren & Helldén, 2009; Othman et al., 2008; Smothers & Goldston, 2010). Students are able to take different interactions into account (Adbo & Taber, 2009; Nahum et al., 2007; Othman et al., 2008; Stevens et al., 2010). *Examples of typical student statements* • Sodium chlorine exists as a molecule (Othman et al., 2008). • Different carbon isotopes exist, which have a different number of protons in the nucleus (Schmidt et al., 2003). • Interactions exist between electrons and nucleus (Adbo & Taber, 2009). • Atoms are immobile, but electrons are mobile in their shells (Adbo & Taber, 2009).	*Differentiated particle concept* Students are able to use a differentiated particle model to explain physical properties and changes of matter (Johnson & Papageorgiou, 2010; Pimthong et al., 2012). Thereby, they dwell especially on the atom structure and the different interactions between atoms (Adadan et al., 2009; Smothers & Goldston, 2010; Stevens et al., 2010; Talanquer, 2009). Macroscopic properties are not attributed to particles any more (Franco & Taber, 2009). *Examples of typical student statements* • Electrons are freely moveable in a metal (Taber, 2005). • The attractive forces between particles are surmounted when water evaporates (García Franco & Taber, 2009; Othman et al., 2008). • Lower temperature means stronger forces between particles (Johnson, 2005; Talanquer, 2009).	*Differentiated particle concept* Students describe a chemical reaction as reorganization of particles and bonds (Mohan et al., 2009; Rahayu & Kita, 2010). In doing so, they are able to describe elementary reactions on the basis of a differentiated particle model and to name bond types in the products of a chemical reaction (Liu & Lesniak, 2005). Students can make statements about the reaction progress only in a small number of chemical reactions (Kermen & Méheut, 2011). *Examples of typical student statements* • Chromate and lead(II)-ions react (Rahayu & Kita, 2010). • Rust arises through chemical reaction of water with iron and oxygen (Pimthong et al., 2012). • All of the NH_4^+-ions and phenol react and are being transposed (Kermen & Méheut, 2011).	*Differentiated particle concept* Students are able to use the concept of conservation of energy for a chemical change (Mohan et al., 2009). Therefore, they make use of their knowledge about different bond types and interactions (Mohan et al., 2009). *Examples of typical student statements* • The energy that is released in a chemical reaction was included in the reactant before (Mohan et al., 2009). • No energy is lost at a chemical change (Mohan et al., 2009).
3	*Simple particle concept* Students describe matter as consisting of particles, which are regarded as the „last divisional part". (García Franco & Taber, 2009; Liu & Lesniak, 2006; Talanquer, 2009)	*Simple particle concept* Students understand particles as a building brick of matter (Johnson & Papageorgiou, 2010; Nakhleh et al., 2005). There is nothing between the particles. The particles are often described as the "last divisible unit" that is why they are often described with macroscopic properties (Adadan et al., 2010; Gómez et al., 2006). The particles are constantly in motion, whereby the motion rate depends on the aggregate state (Adadan et al., 2009; Johnson & Papageorgiou, 2010; Talanquer, 2009). Particles in solids are understood as immobile (Talanquer, 2009). *Examples of typical student statements* • A substance is completely made of particles (Löfgren & Hellden, 2009). • Gas particles are more mobile than particles of a liquid (Tsitsipis et al., 2012). • Particles in solids are closer together than in fluids or in gases (Eilam, 2004). • Solids are static and immobile (Adadan et al., 2009; Talanquer, 2009). • Air is between particles (Adbo & Taber, 2009) • Water is a bunch of little water particles (Nakhleh et al., 2005). • Water is made up of H_2O-molecules and you can call water H_2O (Nakhleh et al., 2005).	*Simple particle concept* Students describe physical properties and changes with the use of a simple particle model (García Franco & Taber, 2009; Löfgren & Hellden, 2009). They transfer the substantial properties and changes to the particle level (García Franco & Taber, 2009; Löfgren & Helldén, 2009). *Examples of typical student statements* • The wax particles melt when wax is heated (Johnson, 2005; Löfgren & Helldén, 2009; Papageorgiou et al., 2010). • Particles have the same properties than the whole substances (Othman et al., 2008; Talanquer, 2009). • Water makes baking soda into little baking-soda-particles (Liu & Lesniak, 2006). • In ice, molecules aren't moving and being stopped, but in fluids, molecules are moving and making the water liquid (Nakhleh et al., 2005).	*Simple particle concept* Students describe a chemical reaction as reorganization of particles. But they have no model which allows them to describe processes during a chemical reaction (Crespo & Pozo, 2004; García Franco & Taber, 2009; Papageorgiou et al., 2010). *Examples of typical student statements* • Hydrogene and oxygene have reacted and formed a new substance: water (Liu & Lesniak, 2006). • Particles are joining together and form a new particle (García Franco & Taber, 2009; Smothers & Goldston, 2010). • New substances arise through interactions between particles (García Franco & Taber, 2009).	*Simple particle concept* Students are able to use the principle of conservation of matter as well as the principle of conservation of the amount of particles in a scientifically correct way (García Franco & Taber, 2009; Mohan et al., 2009; Rahayu & Kita, 2010). *Examples of typical student statements* • The product mass arises as a result of the reactant's mass (Salta & Tzougraki, 2011). • By dissolving salt in water you can taste the salt in the water so it does not disappear (García Franco & Taber, 2009).

2	***Hybrid concepts*** Students describe matter as containing particles as entities embedded in a substance (Crespo & Pozo, 2004; García Franco & Taber, 2009; Gómez et al., 2006; Löfgren & Héllden, 2009; Talanquer, 2009). They consider that between the particles is the actual substance (Gómez et al., 2006; Löfgren & Héllden, 2009; Talanquer, 2009).	***Hybrid concepts*** Students understand particles as a component of matter (Gómez et al., 2006). Between the particles is the actual substance (Papageorgiou et al., 2010; Talanquer, 2009; Tsitsipis et al., 2012). But the students are not able to use their perception concerning particles to explain structure and composition of matter (Johnson & Papageorgiou, 2010). Nevertheless, they are able to distinguish substances and their composition. Thus, they can recognize if a substance is pure or a mixture (Calik et al., 2009; Johnson, 2005). Students understand particles as entities embedded in matter (Johnson, 2005). *Examples of typical student statements* • "Matter is granular" (Talanquer, 2009). • A sugar cube consists of many little sugar pieces, which are compacted together (Nakhleh et al., 2005). • Particles are embedded in a substance like raisins (Johnson, 2005).	***Hybrid concepts*** Students are able to categorize substances and to attribute characteristic properties to these categories (metals, non-metals, salts), therefore students use "actions" or "similarities" to classify substances and matter (Krnel et al., 2005). Students describe physical changes as a modification of the original substance without using the particle model for a reasonable explanation (Krnel et al., 2005; Smothers & Goldston, 2010). Particles that are embedded in matter are often used in explanatory approaches (Ayas et al., 2010). *Examples of typical student statements* • When water evaporates water particles remain as a residuum (Crespo & Pozo, 2004). • Mercury is only a metal in the liquid state (Krnel et al., 2005). • Phase changes arise through heat and energy (Adbo & Taber, 2009).	***Hybrid concepts*** Students recognize chemical reactions through the emergence of a new substance with other properties than the reactants (Liu & Lesniak, 2006). As they do not have a particle perception in order to explain chemical reactions correctly, the following misconceptions appear frequently: (a) Students claim that the products of a chemical reaction were already present in the reagents (Krnel et al., 2005; Papageorgiou et al., 2010). (b) Students claim that the reactants are still present but only their properties have changed (Krnel et al., 2005; Smothers & Goldston, 2010). (c) Students do not recognize the coherence between educts and products. The educts have changed to a new substance or to energy (Kermen & Méheut, 2011; Liu & Lesniak, 2006; Smothers & Goldston, 2010). *Examples of typical student statements* • Rust was already present in the iron and became now visible (Salta & Tzougraki, 2011). • The copper particles have changed to black particles (Crespo & Pozo, 2004). • Mercury arises through a melting metal (Krnel et al., 2005). • Various substances melt to form mercury (Krnel et al., 2005). • All of the acid and bases properties are kind of deleted (Liu & Lesniak, 2006).	***Hybrid concepts*** Students understand that substances can not disappear and that the number of particles has to remain constant in chemical reactions or physical changes (Liu & Lesniak, 2006; Pimthong et al., 2012). Students believe that the mass of a substance is dependant on the position and on the aggregate state of a substance (Othman et al., 2008). The mass of a substance portion can increase when it is compressed. (Treagust et al., 2010). *Examples of typical student statements* • Matter changes when it decreases from liquid to gas (Othman et al., 2008). • Sugar does not disappear during a solution process (Pimthong et al., 2012). • A rusty nail weighs less than a pure nail (Salta & Tzougraki, 2011). • Soda dissolves in water, but when water evaporates soda appears again (Liu & Lesniak, 2006). • Nothing can disappear (Smothers & Goldston, 2010).
1	***Naïve concepts*** Students describe matter as everything that occupies space and that has a mass. They consider that matter is a continuum, which can be portioned, but is not made of particles. They also think that matter can be produced and destroyed (Gómez et al., 2006; Krnel et al., 2003; Krnel et al., 2005; Liu & Lesniak, 2005; Liu & Lesniak, 2006; Löfgren & Héllden, 2009; Talanquer, 2009).	***Naïve concepts*** Students describe structures without the use of the particle concept (Liu & Lesniak, 2006). They consider matter as portionable but continuously build (Ayas et al., 2010; Papageorgiou et al., 2010). Students understand matter as a carrier of properties (Adadan et al., 2009; Talanquer, 2009). *Examples of typical student statements* • The smallest particles in water are water drops: There are many particles, when there are many water-drops (Eilam, 2004). • The pipe consists of wood (Krnel et al., 2003). • A lot of things are metallic (Krnel et al., 2003) • Molecules consist always in the solid state (Tsitsipis et al., 2012) • Matter is continuous (Adadan et al., 2009; Gómez et al., 2006; Talanquer, 2009; Tsitsipis et al., 2012).	***Naïve concepts*** Students do not have any model that allows them to describe physical properties and changes of matter scientifically. They describe only what they have observed (García Franco & Taber, 2009; Liu & Lesniak, 2006;). They use the behavior of prototypes to describe substance properties, e.g. water is a prototype for liquids (Krnel et al., 2005; Othman et al., 2008). *Examples of typical student statements* • Liquids are transparent and always contain water (Talanquer, 2009). • Water disappears during evaporation (Pimthong et al.,2012). • Metals are always like iron (Krnel et al., 2005). • Baking soda melts into little bits, which cannot be seen anymore (Liu & Lesniak, 2006).	***Naïve concepts*** Students do not have any model that is appropriate to describe or to recognize chemical reactions scientifically. In explanation approaches, they describe what they have observed (García Franco & Taber, 2009; Smothers & Goldston, 2010). *Examples of typical student statements* • The color of a liquid has changed (García Franco & Taber, 2009). • Sugar dissolves in water and causes a chemical reaction (Smothers & Goldston, 2010). • Bubbles are made by carbon dioxide (Liu & Lesniak, 2006).	***Naïve concepts*** Students do not observe any conservation of mass in their daily life. They believe that the number of reactants changes with the mass in a chemical reaction for they do not have any particle perception (Löfgren & Helldén, 2009). Thus, substances can disappear in chemical reactions and in physical changes (Mohan et al., 2009; Rahayu & Kita, 2010; Smothers & Goldston, 2010). *Examples of typical student statements* • Wax disappears when a candle burns (Löfgren & Héllden, 2008; Löfgren & Héllden, 2009). • Water is gone when it evaporates (Löfgren & Héllden, 2009). • Naphthalene reduces by reacting with air (Rahayu & Kita, 2010). • Substances can disappear and therefore they become less weight (Adbo & Taber, 2009).

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