Gem and Mineral Tutorial

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What is a Gem?

A gem is a gemstone that has been fashioned—cut, shaped, and/or polished—to enhance its natural beauty. The gemstone is the raw material or "rough"; the gem is the finished product. Most gemstones are minerals, but some are rocks, and a few are the organic products of once-living animals or plants. A gem ruby is created from a piece of the mineral corundum; lapis and jade are rocks; and pearls, amber, and jet are organic products.

What Gems Are Made Of

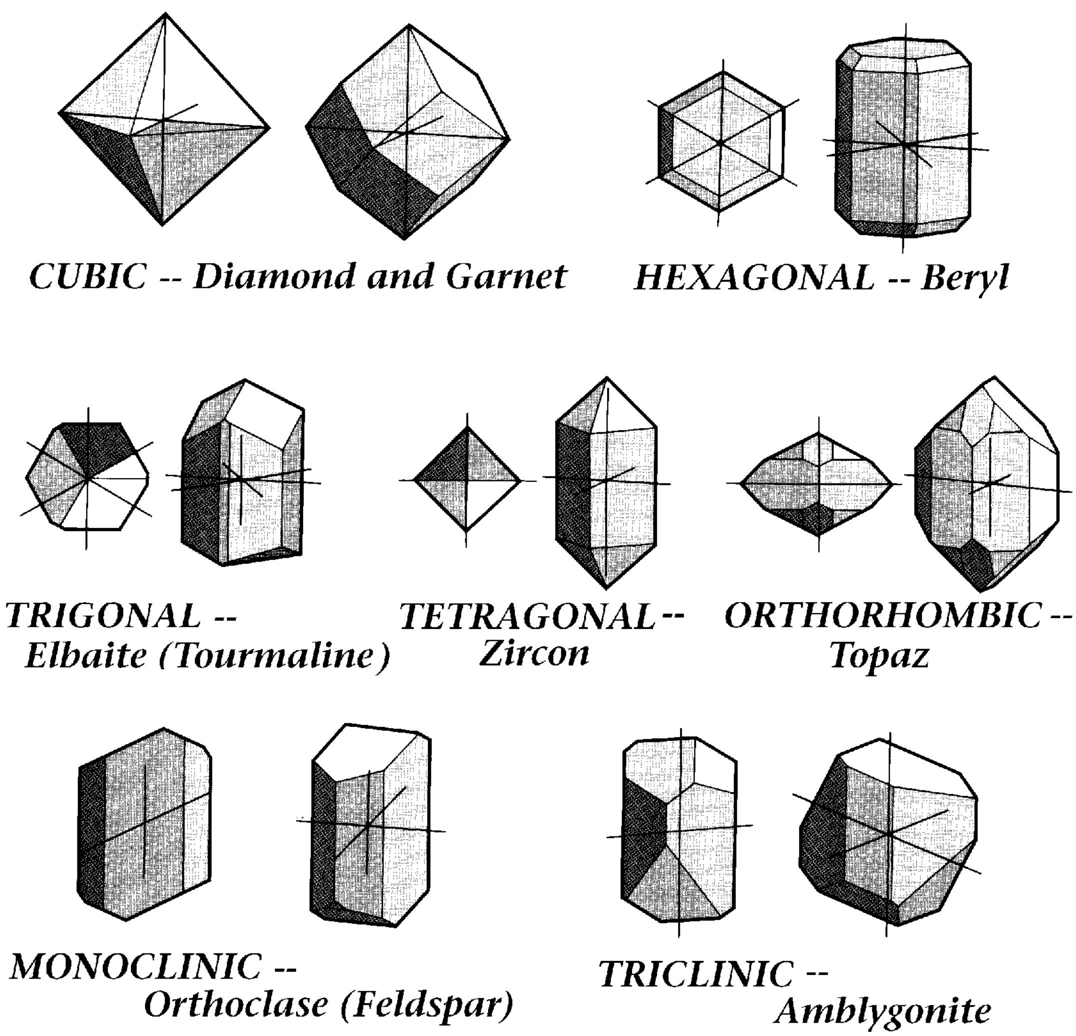
Rocks and Minerals represent two different levels of organization of matter. Atoms are the building blocks for minerals; minerals are the building blocks for rocks; and rocks make up the solid Earth. Rocks are physical assemblages of pieces of minerals. The boundaries between all the grains tends to make rocks opaque, so it is usually their color or occasionally their toughness that makes them attractive as gemstones. Minerals are more frequently valued as gemstones because they can be transparent and fashioned into glittering gems. The fact that minerals are crystalline allows them to form large transparent gemstones that have interesting optical properties.

Being crystalline means that a mineral's constituent atoms—one or more of the 92 naturally-occurring chemical elements—are organized in a regular geometric pattern that repeats in three dimensions to form a solid body called a crystal. One usually recognizes a crystal by its natural flat surfaces called faces. Crystals can be invisibly small or larger than automobiles, but a crystal's properties and atomic organization are the same throughout the entire body. The geometric arrangement of atoms is called the crystal structure. The atoms are linked by chemical bonds—electrical forces and electron interactions between atoms—that literally hold the mineral together and produce its properties.

A mineral also has a chemical composition that can be defined within well-constrained limits, usually by a relatively simple chemical formula. Corundum is natural aluminum oxide, $A1_{2}0_{3}$. Each of the roughly 3,000 mineral species is defined by its chemical composition and its crystal structure.

A well-formed crystal is the external expression of the symmetry of the repeating arrangement of atoms within. The way in which shapes are repeated determines the type of symmetry. A crystal with faces that repeat across a plane (a mirror), about an axis (rotation), or through a point (inversion) contains one (or more) elements of these three basic kinds of symmetry.

For example, a hexagonal green beryl crystal rotated 60 degrees about its center (axis) appears unmoved; it is repeated by six fold rotation. Most pencils, like beryl crystals, have the form of a hexagonal prism. Some minerals have no symmetry, and others have many symmetry elements. The symmetry a crystal can possess is constrained by the ways groups of atoms can be repeated in space to create a solid crystal. There are only seven basic systems of crystal symmetry, which are shown diagrammaticly.



All minerals belong to one of these seven crystal systems. The crystal symmetry is not only helpful in identification, as with the hexagonal beryl, but properties such as hardness and color can vary with direction in the crystal, depending upon its symmetry. Thus, a gem is cut from an individual crystal to take advantage of not only its uniformity as a transparent, cohesive object but, possibly, its special directionally-dependent properties.

Mineral crystals are created by growth from a nucleus, some speck or mineral surface, by additions of successive layers of atoms on the crystal's outer surface. Some minerals, particularly tourmaline among gemstones, manifest this layered growth with concentricly color-banded crystals.

Growth occurs when the temperature, pressure, and chemical environment are favorable; but most mineral crystals, such as the grains in rocks, do not have symmetric form with flat faces because the crystals grow into or against one another. Well-formed crystals are rare because they need not only appropriate and sustained growing conditions but also a space in which to grow, such as a cavity, where growth will be unimpeded. Even then, perfectly symmetrical crystals are rare so this should male you feel better if your models are a bit cockeyed.

The term habit refers to the actual shape of a mineral crystal or aggregate. For example, a common habit for crystals is the prism, a form with parallel sides that looks like an extruded polygon. Some minerals, such as chrysoberyl, grow as multiple crystals, known as twins. Two or more crystals develop in intimate contact, as an "intergrowth," and give the appearance of a single crystal with more symmetry than the mineral possesses, such as manifesting a six-fold rotation axis where there is none. Other minerals form fine-scale, rocklike aggregates, such as nephrite jade or the jasper form of quartz. A mineral's habit may vary, depending on the conditions during crystal growth.

What makes a Gem beautiful?

The source of color is light, its interaction with an object, and our ability to perceive the result. The color we see is the light that is reflected or transmitted and not absorbed. The causes of color in gemstones are many and varied.

If a mineral's color is inherent, it is called idiochromatic, "self-colored." Malachite, copper carbonate, is always green because copper causes the color and is intrinsic to the mineral.

Minerals that owe their color to physical effects, such as internal boundaries and contaminants, are called pseudochromatic, "false-colored." Jasper, a form of quartz with extremely fine grain size, can contain small particles of iron oxide particles (hematite) that make it brick red. Physical scattering of light, described a little later, produces the play of colors in precious opal.

Allochromatic, "other-colored," minerals are generally colorless and transparent in their pure state but develop color with minor changes in crystal composition or from structural imperfections. Such gemstones are the most numerous, intriguing, and difficult to identify by color alone. Substitution of certain transition elements for aluminum in corundum yields a variety of colors: some iron and titanium causes blue sapphire; a little iron alone results in yellow sapphire; a little chromium produces ruby. (Transition elements are chemical elements in the middle of the periodic table whose electron energy transitions can be stimulated by visible light, thus yielding color.) The same element can result in different colors; a minor substitution of chromium for aluminum in colorless beryl produces the spectacular emerald. Other transition elements important in causing color are manganese, copper, and vanadium.

Damage and/or mistakes in the crystal can cause color. Smoky quartz is the result of radiation damage to the crystal. It can be produced by naturally-occurring radioactive minerals adjacent to a quartz crystal or by bombardment with subatomic particles from a nuclear reactor.

Color in some crystals changes with their orientation; the phenomenon is called pleochroism. Sapphires and rubies and pink spodumene are more deeply colored when viewed down the prism axis. Tourmaline gems can have two different colors, depending upon the direction you look through the gem or crystal. Orientation is very important to the appropriate fashioning of pleochroic gemstones.

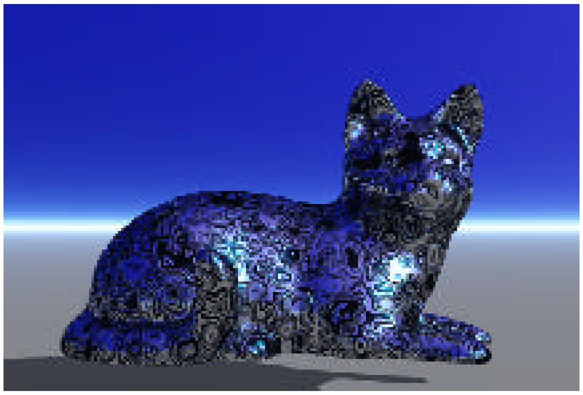
A few gems, notably the ruby, have the property of fluorescence; they can absorb blue and ultraviolet light and reradiate some of the energy in a redder portion of the spectrum. The result is a more intense color with an extra glow that dazzles the eye.

Another important pair of related optical properties of a gem is the way it reflects and range of reflections from metallic to vitreous to resinous to earthy. High luster requires both a smooth surface and a high reflectivity. Polishing of all gems is important in part to improve luster.

Brilliance, on the other hand, is the reflection of light from inside a faceted gem, ("Life" and "liveliness" are used synonymously for brilliance.) This quality is a function of both the cut and the refractive index (R.I.). The R. I. is actually a measure of the velocity of light in the gemstone but is manifested by the degree to which light is bent when entering a substance at an angle and the critical angle at which light is reflected instead. The angles of cut, and thus a gem's proportions, are specifically gauged to the R. I. of each gemstone so that the faceted gem will reflect back from inside the light that enters. All minerals except those of the highest symmetry—cubic—actually have two or three R.I.s and are called "birefringent." Reflectivity is positively correlated with refractive index, and both increase with a substance's density. It is not an accident that the fine transparent gemstones like diamond and sapphire are denser than most minerals. (Density is measured in terms of specific gravity, S. G., the weight of a substance relative to that of an equal volume of water.)

Fire develops in a gem from the phenomenon known as dispersion. The component colors in white light are bent to varying degrees during refraction, with the consequent separation of colors into the rainbow. For two different gems of the same size and cut, the one with greater dispersion will display a better spectrum of colors, or fire; the diamond will have better fire than the quartz gem. In colored gemstones, dispersion is usually masked by the predominant color, so that this property becomes unimportant. Bryce has no controls for creating dispersion automatically but later in the experiments section I have a few tips on creating your own dispersion.

Small to submicroscopic features can produce some surprising visual effects in gemstones. Reflections from parallel layers of transparent materials cause pearly luster. The pearl is built up of concentric layers and gives this luster its name. Hillary Rhode's contributed this beautiful mother of pearl shader to the collection.



The cat's eye effect, chatoyancy (a literal translation from French), is a band of reflected light that appears in certain gemstones. The cat's eye is produced by many straight parallel fibrous inclusions that scatter light perpendicular to their long direction. In corundum, three directions of needles can occur, yielding multiple chatoyancy in the form of a six-rayed star. This is called asterism. The star is visible only when the stone is viewed down the axis of intersection of the inclusions.

Scattering from very small features often imparts colors. In moonstone, thin layers and small elliptical bodies scatter blue light most effectively and yield the characteristic pale blue sheen. Small particles arranged in a periodic pattern will scatter individual colors by optical diffraction, which is observed commonly in bird feathers and butterfly wings. The best example in gemstones is precious opal. A number of other similar scattering phenomena produce colors in stones like fire agate.

Durability, the most important physical attribute in gauging a gemstone's merit, has three aspects: hardness, toughness, and stability. Hardness is the resistance to being scratched and is literally a measure of the strength of the chemical bonds in a substance. In 1822, German mineralogist Friedrich Mohs proposed a scale of hardness consisting of 10 minerals ranked in order of their ability to scratch one another; 1 is the softest, and 10 is the hardest. The scale is relatively linear; that is, each mineral is nearly one value of hardness greater than the previous one. Diamond, 10, is anomalous; it should have a value more like 100 to show its hardness relative to the others. Diamond is held together with extremely strong chemical bonding.

The Mohs Scale

1 Talc
2 Gypsum
3 Calcite
4 Fluorite
5 Apatite
6 Orthoclase
7 Quartz
8 Topaz
9 Corundum
10 Diamond

Quartz, with Mohs hardness of 7, is a common component of dust, so that gemstones softer than 7 are subject to scratching, particularly in rings, where abrasion is commonplace.

Toughness is a gem's resistance to cracking, chipping, and actually breaking. A chief threat to crystals is planes of weakness, representing directions in the crystal structure with relatively fewer or weaker chemical bonds. The result is cleavage—splitting along a plane. Diamond, the hardest mineral, lacks toughness because of its octahedral cleavage planes. Most diamonds in engagement settings will show small chipped corners after years of exposure to everyday wear and tear. Topaz, with a hardness of 8, also lacks toughness. It has one perfect cleavage and therefore is difficult to facet. Some gemstones fracture easily as a result of internal stress, which lowers their strength. Both opals and obsidian can chip easily due to physical or thermal shock. Nephrite jade, with a hardness between 6 and 6.5, is the toughest of gemstones. With a strong interlocking network of fibrous crystals, it can be fashioned into the most intricate shapes. Another tough gem is the pearl; one will not break if dropped on a hard floor, although the gem's hardest is only about 3.

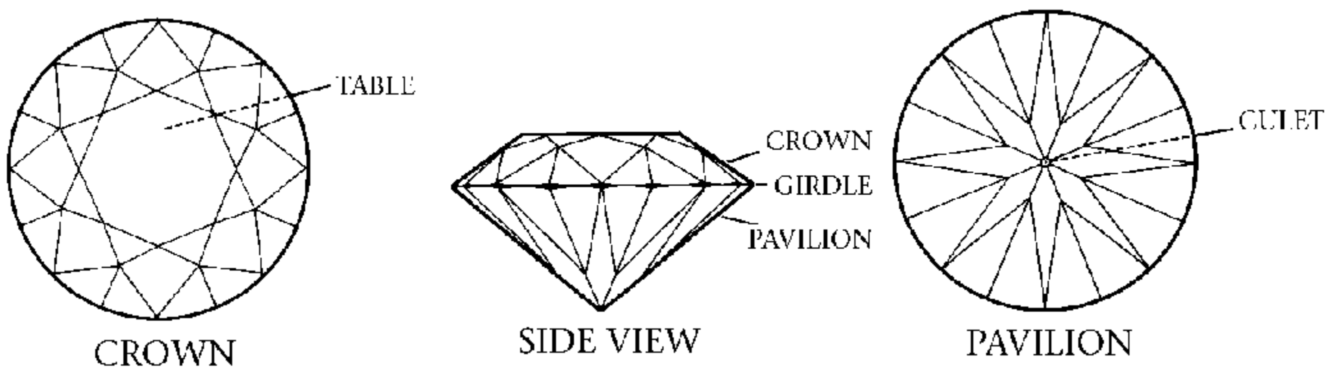
Stability, the resistance to chemical or structural change from deteriorating forces, is an important factor in a gemstone's durability. Opals contain water, and some lose it in dry air; the result is cracks, or crazing, from loss of volume. Pearls are damaged by acids, alcohol, and perfume. Porous gemstones like turquoise can pick up oils and coloring from the skin. The color of some kunzite and amethyst fades on exposure to sunlight. However, the majority of gems are stable in most conditions the wearer is likely to place them.

Cutting and Polishing

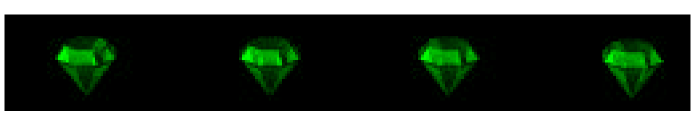
For an opaque gemstone, only the surface properties are important. Such stones are rarely faceted and are more frequently polished to obtain a smooth, rounded surface. The cabochon ("bald head"), a rounded top usually with a flat base, is used for translucent and opaque gemstones and gems displaying optical phenomena such as chatoyancy, asterism, and play of color.

Transparent gemstones are faceted. The process consists of cutting with an abrasive (usually diamond) saw, grinding with abrasives, and polishing facets. Cut also means the shape or style in which a gem is fashioned. Faceting and proper proportioning are essential for revealing the full beauty of transparent minerals, particularly a diamond's fire. Diamond Faceting first appeared in the fourteenth century, but intense study of methods was stimulated by the great nineteenth-century discoveries of diamonds in South Africa. We now know the exact angles which must be present between facets to cause all light incident on the gem to be completely reflected for maximum brilliance. The round brilliant cut with its modifications (oval, pear, marquise, and heart) and the step (emerald) cut are the most popular.

The image below shows the parts of the cut stone on a common round brilliante cut. In the shapes folder is a intersected Bryce model donated by Tim Styles (MonkeyT) which you can take a part to see how to create faceted stones.



The quality of cutting and polishing is another factor in the evaluation of all gems, although particularly significant for diamond. Many dealers will buy poorly faceted or proportioned stones and have them recut with reduction in weight but dramatic increase in value.



Gems and Bryce Experiments

I went through a steep learning curve constructing the gems in Bryce. At first I tried to create reflection by constructing an internal crystal structure, then intersecting that with a gem shape. The results were interesting but not usable. Bryce's built-in reflection and refraction combined with the internal structure to create a white mass as Bryce's internal reflection limit was exceeded. After that I found that changing the refraction setting in Bryce simulated the internal bending of light done at an atomic level by the crystal lattices in a natural mineral.

At the end of this section are tables showing the properties of all the common gem stones, some uncommon ones and an assortment of other interesting minerals that may prove useful in Bryce building.

Refraction in crystals will vary according to the angle the light strikes the object, the crystal axis it is striking, whether the surface is polished or unpolished and whether the light is natural sunlight or artificial. Fortunately this variation usually runs no more than 2 to 4 units on either side of the average value in this table. When creating the objects in Bryce you can change the Bryce RI number up or down to get the effect that looks best in your scene.

Example-- A sphere with all the other parameters set identically will yield ice at 133, quartz at 153, and diamond at 241, by varying only the refraction setting.

One exception to this lack in internal structure would be a cabochon cut star sapphire or ruby. If you wanted to achieve the "star" effect by cutting parallels to its main axis, you would want to place three planes crossing at 60-degree angles to one another, and then intersect this with a flattened oval.

Another thing I discovered from my experimentation was to keep the reflection set low. Ah! you're thinking but jewels are shiny! True for natural jewels, but this is Bryce, and too large a reflection setting will yield white blobs again! The value you use will vary with the amount of lighting in your scene, and the angle at which you are viewing the gem. I would suggest starting with an initial setting of about 25 and tweak it until it looks best in your own scene.

Experiment - Try making a simple red diamond shape with settings of 0, 25, 100 in reflection while holding the refraction steady at 170.)

Turquoise can easily be created by taking a marble preset and altering the matrix to turquoise green and the veins of the marble to a darker grayish turquoise. Then apply this to a stone primitive for a natural turquoise nugget, or a flattened sphere or cube for a gemstone.

Jade can be created in the same way from a preset marble -- just pick one that is mostly matrix with thin veins as gem quality jade is mostly one color with only a slight amount of variation to add interest.

Very attractive images can be made by applying turquoise and jade shaders to poser models or other dfx sculpture. The shapes and shaders folder contain a cabochon turquoise gem and a jade mask.

Opal is noncrystalline, so the gem form is usually cut as a smooth cabochon. The fire of the opal comes from reflections of minerals filling fine fractures within the stone. I tried two methods of creating this effect. The white opal's fire comes from a custom shader that is milky white with bits of color. For the other I created tiny flatten terrains with metallic shaders and arranged them inside a clear oval shape. I tried simple squares with shaders but I think the terrain surfaces break up the light better. See opals in Shapes and Shaders folder.

It is interesting to note that metals even though opaque are still affected by their refraction and reflection. Don't rely on secularity alone to create your metals, for the best results these need to adjusted as well.

Refraction of Precious & Semi Precious Gems

Mineral	Crystal Family	RI	Dispersion	Color and comments
Alabaster	Cubic	1.52	Opaque	lustrous
Alexandrite	Ortho	1.75	Moderate	Changes color in natural & artificial light
Amber	Amorph	1.45	Lustrous	golden yellow to brown
Amethyst	Hexag	1.54	Low	
Aragonite	Ortho	1.53	Opaque/lustrous	white/pink/greenish
Aquamarine	Hexag	1.60	Low	Greenish blue to light blue
Azurite	Monocl	1.73	Opaque	dark azure blue
Beryl	Hexag	1.58	Low	
Red Beryl	Hexag	1.60	Low	Raspberry red
Chrysoberyl	Ortho	1.75	Moderate	
Diamond	Cubic	2.41	High, Superb Fire	
Emerald	Hexag	1.60	Low	intense velvety green color
Epidote	Monocl	1.73	Mod.	yellowish green
Fluorite	Cubic	1.43	Low	multicolor

Garnet	Cubic	1.80	Moderate	ruby red to Kelly green
Heliodor	Hexag	1.58	Low	Golden yellow
Hematite	Hexag	3.22	Opaque	gem form of iron
Jade	Amorph	1.66	Opaque	multicolor
Kunzite		1.67		Lilac moderate
Lapis Lazuli¡	Cubic	1.50	Opaque	Dark blue,
Lepidolite	Monocl	1.51	Opaque	purple mica
Labradorite	Triclinic	1.56	Light scattering & iridescence bluish white	
Malachite	Amorph	1.85	Opaque	banded green and white
Morganite	Hexag	1.56	Low	Purplish pink to peach Peridot
	Ortho	1.66	Moderate	unique lime green color
Onyx Marble	None	1.49	Opaque	
Opal	None	1.56	Low	Diffraction-play of colors
Quartz	Hexag	1.54	Low	
Rhodonite	Triclinic	1.71		
Rose Quartz	Hexag	1.55		
Ruby	Hexag	1.77	Moderate	
Rutilated Quartz	Hexag	1.54	Low	contains rods of golden metallic rutile
Sapphire	Hexag	1.77	Moderate	
Serpentine	Monocl	1.53	Opaque	
Smoky Quartz	Hexag	1.55	Low	
Spinel	Cubic	1.71	Moderate	
Talc	Monocl	1.53	Opaque	lustrous
Topaz	Ortho	1.60	Low	clear, yellow to blue
Tourmaline	Hexag	1.64	Moderate	multicolor within a single stone
Turquoise	Triclinic	1.65	Opaque	
Uvarovite	Cubic	1.84	Medium	green garnet, Kelly green
Rhodochrosite	Hexag	1.83	opaque	pink to red
Zircon	Tetragonal	1.95	High	med to dark blue to colorless
Tanzanite	Ortho	1.70	Moderate	intense blue to blue gray

Refraction of Other Interesting Minerals/Things

Air	None	1.00	Transparent	
Biotite	Monocl	1.54	Opaque	Black Mica
Calcite	Hexag	1.65	Low	white and earthtones
Dolomite	Hexag	1.68	Low	opaque
Glass-window	None	1.52		
Glass-lens	None	1.65		
Halite	Cubic	1.54	Low Milky	
Ice	None	1.30		
Moss Agate	None	1.54	Low	
Obsidian	Amorph	1.48	Opaque	black highly reflective
Water	None	1.33	Liquid	

Refraction of Metallic Crystals

Metal	Family	RI	
Aluminum	Monocl	1.44	
Bronze	alloy	1.18	
Cassiterite	Tetra	4.00	tin
Chrome	Cubic	2.97	
Cinnabar			
Copper	Cubic	1.10	
Gold	Cubic	0.47	
Iron	Cubic	1.63	
Lead	Cubic	2.01	
Magnetite	Ortho	2.02	
Mercury	None	1.62	liquid
Platinum	Cubic	1.82	
Silver	Cubic	0.18	
Steel	Alloy	2.50	

Reflection of Light by Polished Metals
under natural light 589 angstroms

Metal	Percent Reflected	Bryce Number
Bronze	64%	163
Copper	71.3%	183
Gold	84.4%	215
Iron	57%	145
Mercury backed glass	69.9%	178
Nickel	65%	166
Platinum	64.2%	164
Silver	92.6%	236
Steel	55.4%	141
Silver backed glass	89.1%	227
Snow	93%	237

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