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GOLD: PROPERTIES, MINERALS, ALLOYS, USES AND RECYCLING

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Abstract: *The paper presents a brief history of Bronze Age gold to the Middle Ages, as well as its properties, minerals and deposits, alloys, uses and recycling.*
Keywords: *gold, gold ore, gold use, recycling*

1. Short history

Gold has always fascinated people, enriching some or ruining others, provoking wars or facilitating alliances, and leading to the rise of some empires or the disappearance of others. It has been so present in human life that it is mentioned 417 times in 189 verses of Holy Scripture, beginning with *Genesis 2:11* and ending with *Revelation 21:18.* It was one of the three gifts that the Magi gave to Baby Jesus, along with myrrh and frankincense: gold like a king, incense like a God, and myrrh like a man who was to die and be embalmed. U.S. researchers, whose professional integrity cannot be questioned, say there is evidence of the use of gold as early as 6,000 years ago, citing the following more important data [1]:

4000 B.C. A culture, centered in what is today Eastern Europe, begins to use gold to fashion decorative objects. The gold was probably mined in the Transylvanian Alps or the Mount Pangaion area in Thrace.

3000 B.C. The Sumer civilization of southern Iraq uses gold to create a wide range of jewelry, often using sophisticated and varied styles still worn today.

2500 B.C. Gold jewelry is buried in the Tomb of Djer, king of the First Egyptian Dynasty, at Abydos, Egypt.

1500 B.C. The immense gold-bearing regions of Nubia make Egypt a wealthy nation, as gold becomes the recognized standard medium of exchange for international trade. The Shekel, a coin originally weighing 11.3 grams of gold, becomes a standard unit of measure in the Middle East. It contained a naturally occurring alloy called electrum that was approximately two-thirds gold and one-third silver.

1350 B.C. The Babylonians begin to use fire assay to test the purity of gold.

1200 B.C. The Egyptians master the art of beating gold into leaf to extend its use, as well as alloying it with other metals for hardness and color variations. They also start casting gold using the lost-wax technique that today is still at the heart of jewelry making. Unshorn sheepskin is used to recover gold dust from river sands on the eastern shores of the Black Sea. After slucing the sands through the sheepskins, they are dried and shaken out to dislodge the gold particles. The practice is most likely the inspiration for the „Golden Fleece".

1091 B.C. Little squares of gold are legalized in China as a form of money.

560 B.C. The first coins made purely from gold are minted in Lydia, Asia Minor.

344 B.C. Alexander the Great crosses the Hellespont with 40,000 men, beginning one of the most extraordinary campaigns in military history and seizing vast quantities of gold from the Persian Empire.

300 B.C. Greeks and Jews of ancient Alexandria begin to practice alchemy, the quest of turning base metals into gold. The search reaches its pinnacle from the late Dark Ages through the Renaissance. 218–202 B.C. During the second Punic War with Carthage, the Romans gain access to the gold mining region of Spain and recover gold through stream gravels and hardrock mining. 58 B.C. After a victorious campaign in

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Gaul, Julius Caesar brings back enough gold to give 200 coins to each of his soldiers and repay all of Rome's debts.

50 B.C. Romans begin issuing a gold coin called the Aureus.

476 A.D. The Goths depose Emperor Augustus, marking the fall of the Roman Empire.

600–699 A.D. The Byzantine Empire resumes gold mining in central Europe and France, an area untouched since the fall of the Roman Empire.

742–814 A.D. Charlemagne overruns the Avars and plunders their vast quantities of gold, making it possible for him to take control over much of Western Europe.

1066 A.D. With the Norman Conquest, a metallic currency standard is finally re-established in Great Britain with the introduction of a system of pounds, shillings, and pence. The pound is literally a pound of sterling silver.

1250–1299 A.D. Marco Polo writes of his travels to the Far East, where the „gold wealth was almost unlimited".

1284 A.D. Venice introduces the gold Ducat, which soon becomes the most popular coin in the world and remains so for more than five centuries.

1284 A.D. Great Britain issues its first major gold coin, the Florin. This is followed shortly by the Noble, and later by the Angel, Crown, and Guinea.

1377 A.D. Great Britain shifts to a monetary system based on gold and silver. 1511 A.D. King Ferdinand of Spain says to explorers, "Get gold, humanely if you can, but all hazards, get gold," launching massive expeditions to the newly discovered lands of the Western Hemisphere.

2. Properties of gold

Gold was one of the first metals used by man, along with copper, the name being given by the Romans (*aurum*), where *aura* means *gold*, brightness or light. It has a bright yellow color, warm and pleasant, being the most malleable and ductile of all metals. So malleable that a 1 m^2 semi-transparent sheet can be beaten from a gram of gold and so ductile that it can be pulled into extremely small thick wires. It is a good conductor of heat and electricity, melts at 1,064°C, boils at 2,970°C and has a density of 19.30 g/cm^3, close to that of tungsten (19.25). As a result, tungsten was used to counterfeit gold, by plating it with noble metal or by drilling a gold ingot and plugging the hole with a tungsten rod. As a miscellaneous fact, of all metals, the lowest density is lithium (0.53 g/cm^3) and the highest is osmium (22.59 g/cm^3).

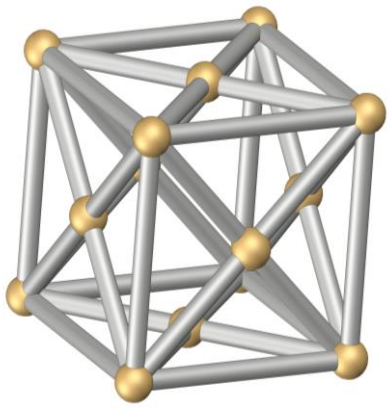

Figure 1. Crystal lattice of gold

Like all metals, solid gold has a crystalline structure, meaning that its atoms are distributed in the nodes of an elementary crystal cell called *a cubic lattice with centered faces.* This network consists of 14 atoms, of which 8 in the corners of the elementary cell and 6 in the centers of the faces of the cube. The density of the atoms in the network is 75% (*Fig.1*). Gold is resistant to the oxidizing and corrosive action of most chemicals, being attacked only by royal water, a mixture of nitric acid and hydrochloric acid, in a volume ratio of 1: 3. It is insoluble in nitric acid, which dissolves silver and base metals, a property used for refining gold and confirming it in various metal objects (*acid test).* It dissolves in alkaline sodium cyanide solutions, a property on which its extraction from poor ores is based by the cyanide process, invented in 1887 in Glasgow, which ensures an extraction yield of 97%. Also based on this property is the coating of metal objects with a thin layer of gold, through the electrochemical galvanizing process. Based on this method, some workers in the electrolytic refining sectors of gold during communism in our country have subtilized significant amounts of noble metal through a simple disarming trick. The operator only had to own a gold cigarette case, which he declared at the entrance in exchange, then tied it to the cathode of the electrolysis tank. A layer of 24 carat gold was quickly deposited on the cigar case. No one weighed the tobacconists at the entrance or exit of the exchange, so modern holoangars only had to turn to complicit jewelers to supply them with other tobacconists. This object was used because it had a larger volume and mass than jewelry, less worn by men. Gold dissolves in mercury, forming a solid solution called amalgam, which is an older extraction process with an extraction yield of 60–75%. The amalgam is heated in

a retort, the mercury is evaporated and a spongy material containing gold and silver, called *burnt gold*, is obtained [2, 3, 4, 5].

The mechanical properties of gold are weak except for plasticity. Instead, the technological ones are goods, it can be processed by casting, plastic deformation and light gluing, using copper or silver, and as a protective flux borax.

3. Gold minerals and deposits

Gold is found in the earth's crust, especially in its native state, but also in the form of combinations with silver, platinum and tellurium. The main minerals of gold are [6]:

- **Calavera** ($AuTe_2$): Au – 43,6%, Te – 56,4%, Ag – 1%.
- **Silvanit** [$(AuAg)_2Te_4$]: Au – 34,37%, Ag – 6,27%, Te – 59,36%.
- **Nagyágit** [$Pb_3(PbSb)_3S_6(AuTe)_3$]: Au – 8,18%, Te – 15,89%, Sb – 5,06%, Pb – 60,22%, S – 10,65%.
- **Krennerit** (Au_3AgTe_8): Au – 34,37%, Ag – 6,27%, Te – 59,36%.
- **Petzit** (Ag_3AuTe_2) : Au – 25,38%, Ag – 41,71%, Te – 32,90%.

All these minerals were discovered in the sec. XIX in the Săcărâmb gold deposit, except for the calavera that was highlighted in 1861 in the Calaveras region of California. The silvanite was discovered in 1835 by the Swiss geographer and crystallographer Lois Necker de Saussure, the petzite in 1842 by the Austrian chemist Wilhelm Petz, the nagyágite in 1845 by the Austrian naturalist Franz Müller, and the krennerite in 1848 by the Hungarian mineralogist Joseph Krenner.

Two types of deposits are known to contain significant amounts of gold, namely primary deposits and secondary deposits. The primary deposits are of hydrothermal origin, being associated with quartz and pyrite (*stupid gold!)* and are presented in the form of veins or as gold scattered in rocks. They were formed by the crystallization of hot solutions produced in the process of cooling magma from inside the Earth.

The secondary deposits were formed by the erosion in the superficial area of the terrestrial crust of the filonian or disseminated type deposits, accumulating in the sedimentary deposits at the level of the alluvial terraces or in the sediments at the bottom of the rivers and seas. In addition to gold, there are other metals or precious stones in these alluvial deposits with densities higher than those of quartz (2.65) with which they are associated: uranium, thorium, tin, zirconium, titanium, ruby, sapphire and diamond. As with other useful substances, these alluvial accumulations become ore deposits. The alluvial deposits found along the watercourses were the main sources of gold in antiquity for Egypt, Mesopotamia, Lydia (today in Turkey), Persia, India and China.

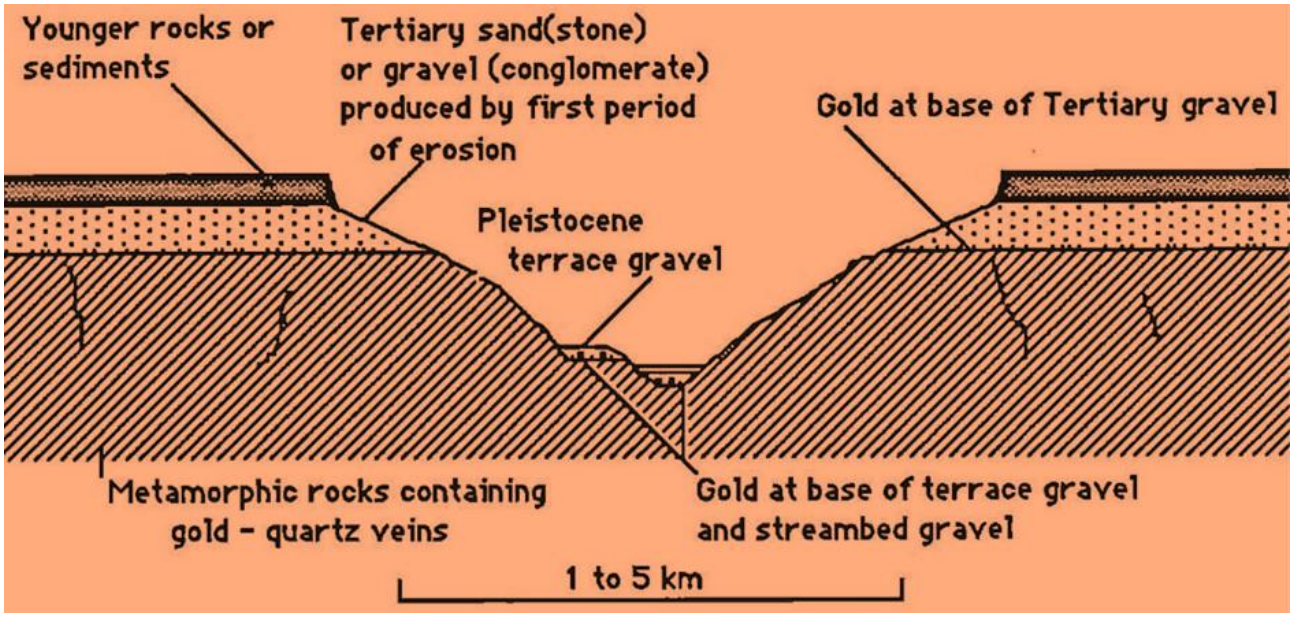

Figure 2. Formation of an alluvial deposit

Experts estimate that the world's gold reserves are currently about 50,000 tons, of which almost 70% are located in 10 countries (Table and *Fig.3*). In Romania, the gold mines were closed, as unprofitable, in 2006, but in the basement of the country there are still important reserves in the Gold Quadrangle of the

Apuseni Mountains and in the Baia Mare mining basin. In the absence of official data, it is difficult to assess the gold reserve left in the basement, which is certainly quite significant.

In Romania, about 2,070 tons of gold were extracted over time, as follows: pre-Roman period (before 106 A.D.) – 10%; Roman period (106-270) – 24%; the Middle Ages (270-1492) – 24%; period of the Habsburg Empire (1492-1918) – 27%; the interwar period (1918-1945) – 4%; the communist period (1945-1989) – 9%; post-communist period (1989-2006) – 2%. The largest amount of gold on the territory of Romania (actually from Transylvania, Banat and Maramureş) was extracted in the period 1492–1918 by the Habsburg Empire (27%).

No. crt.	Country	Reserves, t	No. crt.	Country	Reserves, t
1.	Australia	10.000	6.	Brazil	2.400
2.	Russia	5.300	7.	Peru	2.100
3.	South Africa	3.200	8.	China	2.000
4.	USA	3.000	9.	Canada	1.900
5.	Indonesia	2.600	10.	Uzbekistan	1.800

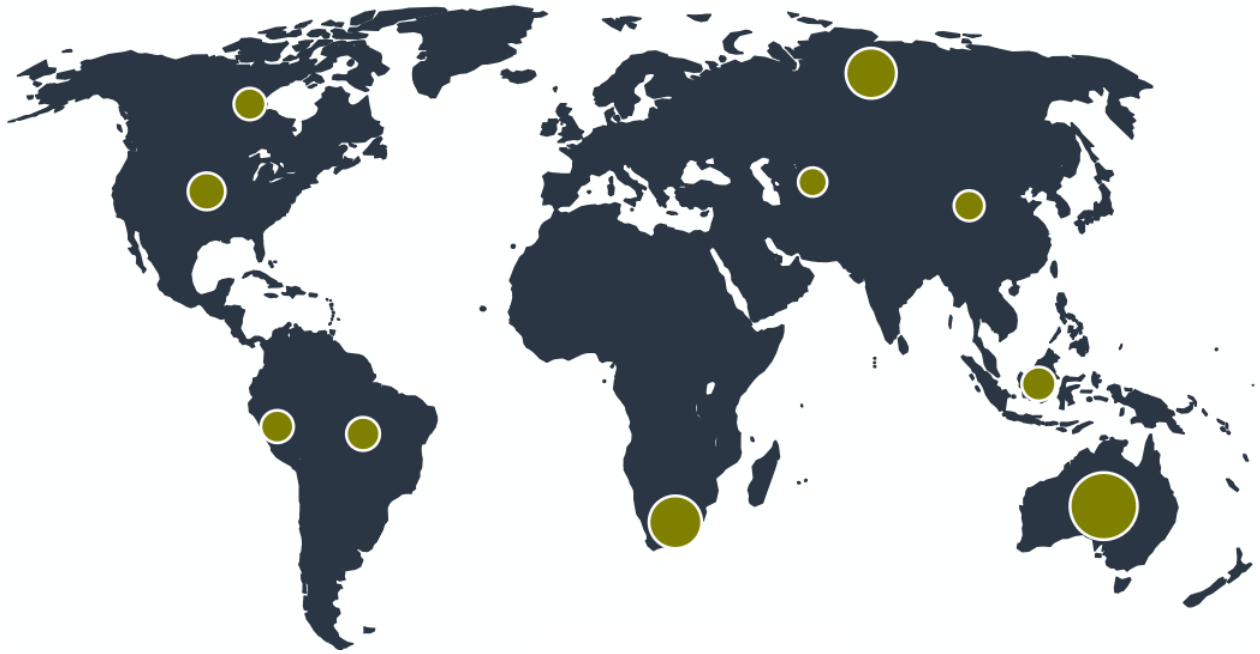

Figure 3. World's major gold reserves [7,8]

4. Gold alloys

Because gold is too soft to withstand long-term use, it is alloyed with other metals to increase hardness and wear resistance. Also, the alloying elements lead to a variety of shades or colors. The amount of gold in an alloy equal to 24^{th} of the total mass is called *the carat.* So 24 carat gold is pure gold.

Carats	24	22	20	18	16	14	12	10	8	6	4	2	0
% Au	99,99	91,67	83,34	75,01	66,68	58,35	50,02	41,69	33,36	25,03	16,7	8,37	0
Thousand ths	999	917	833	750	667	584	500	417	337	250	167	84	0

Silver and copper are the main metals with which gold is alloyed, but it can also be alloyed with platinum, nickel, zinc, manganese and palladium, obtaining alloys with different destinations, properties and colors. Only 24 and 18 carat alloys are recognized as universal. The others are considered to be specific to the culture of certain countries or regions of the world, as follows: they have **22k** – UK, Asia; Au **20k** – Asia; They have **15k** (625 ‰) – Great Britain, Australia, New Zealand; Au **14k** – Europe, Asia, USA, Turkey; At **12 k** – USA, South Africa; Au **10k** – USA, South Africa; Au **9k** (375 ‰) – Europe, Australia, New Zealand; Au **8k** – Germany.

4.1. Gold alloys for jewelry

Pure gold cannot be used in the manufacture of jewelry, having a very high malleability. To increase the hardness and resistance to breakage and wear, it is especially alloyed with copper and silver, but also with zinc, iron or aluminum. The first jewelry made of gold and silver alloys appeared in ancient and then pre-Columbian civilizations. Today, most gold jewelry is made of 18 carat alloys, with 9 different shades:

- **Yellow gold:** Au – 75%, Ag – 12.5%, Cu – 12.5%.
- **Rose gold:** Au – 75%, Cu – 20%, Ag – 5%.
- **White gold:** Au – 75%, Ag – 18.5%, Zn – 5.5%, Cu – 1%.
- **Gray gold:** Au – 75%, Fe – 17%, Cu – 8%.
- **Red gold:** Au – 75%, Cu – 25%.
- **Green gold:** Au – 75%, Ag – 25%.
- **Blue gold:** Au – 75%, Fe – 24.4%, Ni – 0.6%.
- **Purple gold:** Au – 75%, Al – 21% (can be assimilated with **Au 18k**).
- **Black gold:** White gold plated by rhodium plating.

Currently about 53% of world gold production (3,300 t/year) is used in jewelry manufacturing. As nickel used in the alloys of watch cases and bracelets has been found to cause contact dermatitis in one in ten people, the European Union recommends giving it up.

4.2. Dental gold alloy

Dental alloys are standardized internationally by the standards established by ISO 22674:2016. Based on this standard, the following dental gold alloys have been standardized in Germany [9]:

Type	Gold, %	Silver, %	Platinum, %	Palladium, %	Copper, %	Zinc, %
A	87,5	11,5	–	1.0	–	–
B	75,8	15,0	1,4	3,3	4,1	0,4
S	79,3	12,3	0,3	1,6	5,5	1,0
M	74,8	13,5	4,4	2,0	4,1	1,2
M0	65,6	14,0	8,9	1,0	10,0	0,5

They melt at 860–1,080°C, have a breaking strength of 30–59 kg/mm^2, a density of 15.6–17.4 g/cm^3 and a relative elongation at break of 34–43%.

5. Uses of gold

Due to its rarity, beauty and properties, gold has been used as an exchange since ancient times. Early transactions were made with gold or silver pieces, easily portable and divisible. Later, gold coins were minted, which circulated even after the printing of paper banknotes. The banknotes were backed by a safe-keeping stockpile of gold, as the United States did by using *the gold standard*, storing a quantity of precious metal for paper dollars in circulation. According to this standard, anyone could exchange the banknote with its gold plating, but the process proved to be too cumbersome and was abandoned. Gold coins are no longer used in financial transactions, but are popular ways of investing or are issued for commemorative purposes. Today, much of the world's gold reserves are held in national banks in the form of bullion, so that in the event of a financial crisis it can be converted into foreign currency, guaranteeing the liquidity of the holding countries. The official gold reserves of over 100 tons were thus distributed in March 2022 [10]:

Country	Reserves, t	Country	Reserves, t	Country	Reserves, t
USA	8 133	Portugal	383	Venezuela	161
Germany	3 358	Kazakhtan	368	Philippines	156
Italy	2 452	Uzbekistan	337	Singapore	154
France	2 436	Saudi Arabia	323	Brazil	130
Russia	2 302	United Kington	310	Sweden	126
China	1 948	Lebanon	287	South Africa	125
Switzerland	1 040	Spain	280	Egypt	125
Japan	846	Austria	280	Mexico	120
India	760	Thailand	244	Libya	117

Netherlands	612	Poland	229	Greece	114
Turkey	431	Belgium	227	South Korea	104
Taiwan	424	Algeria	174	Romania	104

Gold also has many industrial uses, the most important being in the manufacture of electronic products. They operate with very low voltages and currents, which can be easily interrupted by corrosion at the contact points. With very good electrical conductivity and corrosion resistance, gold is an extremely reliable element used in connectors, switching contacts, printed circuits, relays, solder joints and wires or conductive strips. All of this can be found in mobile phones, standard computers, laptops, camcorders, memory cards, global positioning systems (GPS) and satellites. About 200 tons of gold are consumed annually for the manufacture of these products, from which almost nothing is recovered. Almost a billion mobile phones are produced every year, with a lifespan of about two and very few being recycled. The cost of gold in a mobile phone is 50 cents, so recovering it is not cost effective. The same is true of other electronic products.

The construction of satellites or spacecraft, in which the possibility of lubrication, maintenance and repair is ruled out, could not be achieved without the use of gold, which is a reliable conductor and connector. Many parts of spacecraft are also covered with gold-plated polyester foil, which reflects infrared radiation, ensuring the stability of the interior temperature. Without this protection, the dark parts of the vehicles would absorb too much heat. Gold also reduces the friction of moving mechanical parts, replacing organic lubricants, which would volatilize in the presence of cosmic radiation. With a very low shear strength, the gold atoms slide easily on the surfaces of moving parts, ensuring very good lubrication.

Gold has applications even in medicine, not only in dentistry, but also as a medicine. Injections with weak solutions of sodium aurothiolate ($C_4H_4AuNaO_5S$) or aurothioglucose ($C_6H_{11}AuO_5S$) are used to treat rheumatoid arthritis, pemphigus vulgaris (autoimmune disease that causes fluid bubbles and skin ulcers) and dermatitis. The particles of a radioactive gold isotope are implanted in tissues for the treatment of certain types of cancer. Also, small amounts of gold are used to treat lagophthalmia, a condition that is manifested by the inability of the upper eyelid to cover the eye, which remains open during sleep. The gravitational force of the gold particles helps the eyelid to close completely. Many surgical instruments, electronic equipment, and life support devices contain small amounts of gold, which is extremely reliable and compatible with living tissues. The list of gold uses can continue with the medals of the winners of major sports competitions and school Olympics, Nobel, Oscar, Grammy or other awards, but also with some church objects of worship. The snobbery of the rich has gone so far that some people drink champagne with 24-carat (0.000125 mm) inert organic gold microparticles at exorbitant prices or order gold dusted food, especially in luxury restaurants in Saudi Arabia, France and the USA. Saudi princes drive gold-plated luxury cars, which defies any ethics. It is estimated that today there are about 200,000 tons of gold above the ground, which would fill a cube with a side of 21.8 meters.

6. Gold recycling

It is estimated that about 1,100 tons of gold are recycled annually, which is 33% of the world's 3,300 tons of consumption. 90% of jewelry, ingots, coins and dental gold and 10% of industrial waste are recycled. Recovering gold from industrial waste costs less than extracting it from ores and is less polluting, but 2/3 of what could be recycled is dumped in landfills. There are countries that do not have gold deposits, but recover the precious metal from waste, covering their domestic consumption. Most European industrial waste from which gold could be mined, as well as other deficient metals, is shipped for nothing to Asia or Africa, losing billions of euros.

Country	**Recycled gold, t**	**Country**	**Recycled gold, t**
China	222,1	Japan	48,2
India	103,1	Egypt	45,9
Turkey	77,4	United Kington	40,7
Italy	67,5	Russia	37,6
United States	56,4	South Korea	32,9

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