Exposure: Lead in Philadelphia

Chloe Glynn
H. H. Furness High School

Abstract

Despite being relatively common in the Earth's crust, lead in the natural world is rarely at high enough concentrations that its toxicity becomes important for humans. However, because of lead's low melting point and malleability, it was a desirable metal in early history. Advances in mining, smelting, and distribution of lead concentrated it in such quantities that it resulted in one of the earliest "industrial" diseases associated with a profession. Because it is so reliant on technology, sources of lead poisoning varying widely by history and geography. Whether wealthy Romans, families of Japanese samurai, or Black homeowners in Philadelphia, there is a complex social history for each case of lead exposure that can help guide remediation. The "exposure model" of disease organizes research from social and biological sciences to explain how an environment was contaminated, how the toxin entered and changed a body, and how it progressed to the clinical disease stage. Ninth grade environmental science students at Furness HS will use this model to research why children in Philadelphia are at greater risk for lead poisoning and what can be done to prevent it.

Keywords
Lead, environmental hazards, industrial disease, exposure model of disease, children's health, environmental justice, Philadelphia history

Unit Content

Chemical Properties and History

Lead is a soft, silvery-white metal, the 34th most abundant element in the Earth's crust. It is relatively easy to extract and use due to its low melting point. Other chemical properties include ductility, being a poor conductor of heat and electricity, good corrosion resistance, and malleability, i.e. the ability to be molded (Snodgrass, 1986). This last property is the origin of its Latin name and chemical symbol, *plumbum*, or, *Pb.* In ancient Rome, the word "plumbum" referred to any malleable metal (Blum, 2016) and shares etymological history with the word "plumbers," the Latin name for people who worked with such metals.

Malleability, a low melting point, and the ease of extracting lead from its ore made it one of the most used metals in early history (Needleman, 1999). Lead glazed Egyptian pottery has been dated to 7000 B.C.E.. Smelting, a metallurgical invention that induces a chemical reaction to purify ore, was used to produce a lead-beaded necklace discovered in Anatolia, Turkey estimated to be 6,000 – 8,000 years old. Another major marker in human civilization, the oldest known lead mine, dates to around 6,500 B.C.E in Turkey, predating the Bronze Age by about three millennia. The establishment of

Phoenician mines documents their expansion across the Mediterranean and indicates a demand for metals informed their colonial priorities (Snodgrass, 1986).

These colonial ambitions for metal were subsequently acquired by the Roman empire, whose slave-operated mines and smelteries in Spain and Greece were so large as to introduce atmospheric lead detectable in the ice record of Greenland (Needleman, 1999). "The Mining of the Romans in Spain" by T. A. Rickard in 1928 traces Iberian mineral wealth to Biblical times and includes a then-contemporary description of Roman technological innovations for improving extraction,

> "…pits … penetrate for several furlongs [one furlong is ~200m] not only horizontally but in depth; and, extending their subterranean galleries in different directions, … they raise the ore which yields their gain."

When encountering ground water,

> "This machine [Archimedes screws] … with the application of moderate effort can lift an astonishing mass of water and will easily discharge on the surface the whole volume of such streams…".

Although the imperial aim in those mines was largely for extraction of gold and silver, litharge deposits at Rio Tino indicate lead was also refined on site. Cheap and industrially useful, lead in ancient Rome had several applications. Perhaps most famously used in the extensive system of leaded pipes that gave plumbers their name, it was also used in cosmetics and condiments. It was a preservative in wine distributed across the Roman empire, and it was a substantial component in metal cups, plate ware, pots and pans (Lewis, 1985). In the *Apicius* cookbook from the 5th century C.E., nearly 100 of the 450 recipes call for a concentrated grape sweetener whose flavor partially resulted from being boiled in leaden pots (Ouellette, 2021). With their unprecedented capacity for metal extraction, refining, and production of consumer goods, Dr. Jerome Nriagu estimated that daily lead ingestion of Roman elites was between 35 – 250 mg/day (1983). This consumption may have had biological consequences that shaped the course of Western history.

Lead is an acute biotoxin with no safe level of exposure (WHO, 2023). Several ancient sources document knowledge of lead's toxicity. Xenophon (434–359 BC) wrote that "the smoke of lead mines in Attica was harmful to human health" (Makra, 2019). The 3rd century B.C.E historian, Nicander, wrote in his *Alexipharmaca* of, "that gleaming, deadly white lead" (Montgomery, 2010). Lewis (1985) claims ancient Romans were aware lead could induce "serious health problems, even madness and death." Even Hephaestus, Roman god of smiths, seems afflicted by symptoms of lead poisoning, including lameness and impotence (Aterman, 1999). Whether due to its noxious fumes or deleterious health effects, lead smelting was first banned from the city of Rome and then from all of Italy, consigned to provinces where the effects of acute lead poisoning were observed most readily in the slaves consigned to the back-breaking labor of the lead mines (Lewis, 1985).

While there have been many suggestions for the decline of Rome, including Christianity, the degeneracy of its military and a shortage of manpower (Scarborough, 1984), S. C. Gilfillan wrote an article in 1965 acknowledging, “that the fall of Rome was really a net result of many causes” and went on to revitalize a 1909 proposition (Kobert) that one of those causes was lead poisoning (Gilfillan, 1965). Arguing from existing archeological records, Gilfillan observed that Roman culture, a product of its upper classes, declined markedly around the same time the population size of its elites was in rapid decline. Both of these declines coincided with the introduction of lead-based Grecian cookware in 150 B.C.E., as well as an end to restrictions around women drinking wine. Symptoms of lead poisoning recorded in Roman oligarchs includes low sex drive, sterility, and miscarriage. Jerome Nriagu expanded this list of symptoms in 1983 to suggest “the conspicuous pattern of mental incompetence that came to be synonymous with the Roman elite” was a result of lead poisoning (Nriagu, 1983).

The hypothesis is contentious. There is a powerful *romance* around the “enticing vices” of civilization contributing to its downfall (Montgomery, 2010), the decadence of Nero playing the fiddle in leaden armor as his city burned (Lewis, 1985). Caligula was retitled “The Mad” for his many outrages, including appointing his horse a senator and eating pearls. While permanent mental impairment is indeed a symptom of elevated childhood lead exposure (Byers and Lord, 1943), detractors of the idea cite many competing ideas, including Nriagu’s use of primary source material (Scarborough, 1984).

John Scarborough, a noted classicist, undermines the hypothesis on the basis of sloppy scholarship. In his 1984 essay review, Scarborough takes page 330 from Nriagu’s 1983 paper and systemically corrects mistranslations, mis-citations, and one misuse of an umlaut. Despite the numerous mistranslations and mis-citations by someone with a Ph.D. in geochemistry rather than classics, every ancient source taken issue with is still concerned with lead and its deleterious effects.

Scarborough’s attempt at refuting content is via translation of Cato’s 160 B.C.E. recipe for preparing Greek-style wine where only the “must,” freshly crushed fruit juice, is boiled in a leaden vessel. He writes, “If lead contamination could occur in Cato's wine, it would not happen with the short boiling time of the must.” Yet he acknowledges via Columella and Pliny in the next paragraph that, “sapa was used to lengthen the life of the stored wine, and … it can be argued that lead absorbed in the boiling down of the grape syrup (if a lead vessel were used) would act as an enzyme inhibitor.” The same ancient authors are specifically mentioned in support of Gilfillan’s 1965 proposal with elaboration, “Cooking involving heat greatly heightens the take-up of lead, especially if the pot be scraped from time to time” and “ancient writer Columella said this scraping had to be done in making grape syrup." "Can one show lead poisoning among the Romans?" Scarborough asked in 1984. By 2010, the answer was emphatically, "yes."

Another point of detraction in "lead as a downfall of Rome" is that skeletal lead levels in the bones of Imperial Romans are not universally high (Figure 1; Montgomery, 2010). The 2010 meta-analysis paper reviewed 200 skeletal records from thirty-three burial sites in Britain, Ireland, and Rome and found a wide range median lead concentration in human dental enamel. When comparing lead in dental enamel to the more familiar blood lead levels, the conversion used in the paper is relatively simple;

> "The blood lead level required to produce an enamel lead concentration of 0.07 mg kg^{-1} is estimated to be 0.7 μg dL^{-1} (i.e. a ratio of μg dL^{-1} blood:mg kg^{-1} enamel of ~10:1)."

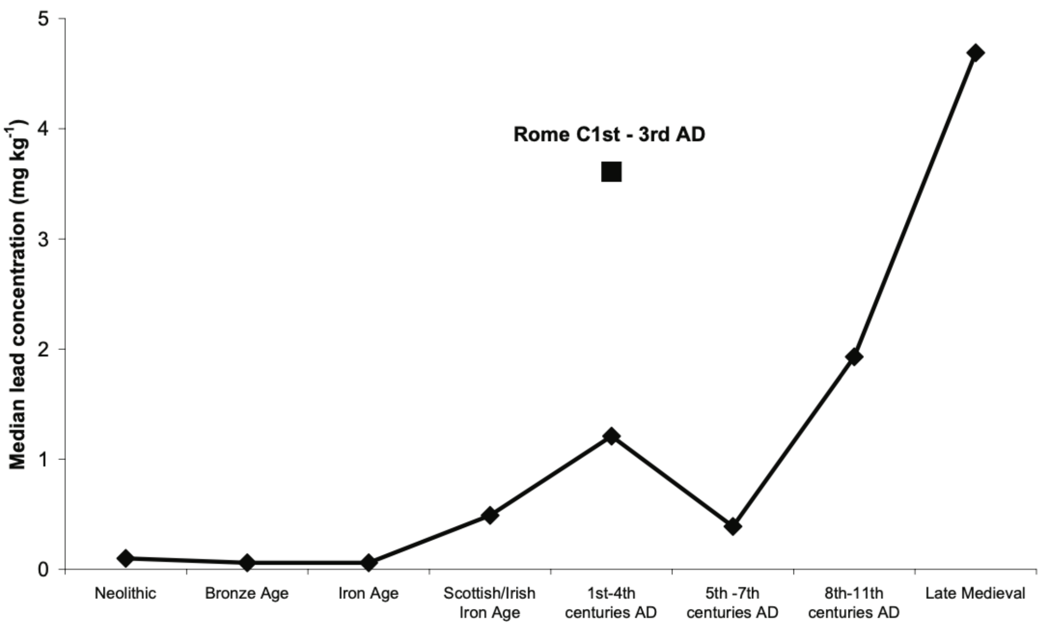


Figure 1. From Montgomery et al (2010) showing median lead concentration of human dental enamel in Britain with 1^{st}-3^{rd} century Roman dental lead median for comparison

Of thirty-three burial sites sampled in this paper, three were from Rome, with a mean dental enamel lead concentration of ~3.8 mg kg^{-1} (Figure 1). This converts to a mean blood lead level of 38 μg dL^{-1}, well above the current threshold for lead poisoning. Of the seventeen Roman samples, all but two had dental enamel greater than 0.5 mg kg^{-1}, indicating a blood lead level of at least 5 μg dL^{-1} in 88% of sampled Romans.

Furthermore, these samples were taken from two cemeteries which, "probably housed only lower-class individuals. It is therefore possible that the lead concentrations observed are not fully representative of all groups of Imperial society." Chiefly not represented in this study are the elite Romans at the center of the hypothesis as those responsible for the cultural and imperial management of Roman society and thus its possible decline.

Another detraction from a 2014 study by Delile et al. attempted to quantify lead exposure from natural and anthropogenic sources using sediment from the Trajanic harbor basin. Constructed in 42 C.E. by Claudius, this major engineering project collects outflow from the Tiber River which would have carried sediment from the leaden pipes of Rome. Analyzing 95 sample cores representing nearly 1000 years of history, the authors found that lead levels in Roman tap water were one-hundred times greater than in surrounding spring water at the start of the Common Era and into Medieval times. ; however, the authors write in their conclusion, with no additional justification, "Lead pollution of 'tap water' in Roman times is clearly measurable, but unlikely to have been truly harmful." Another paper elaborates on this hypothesis that the spring water from the local mountains would have had high concentrations of calcium carbonate which would have created a protective litharge within the pipes (Riva et al., 2012).

Industrial History

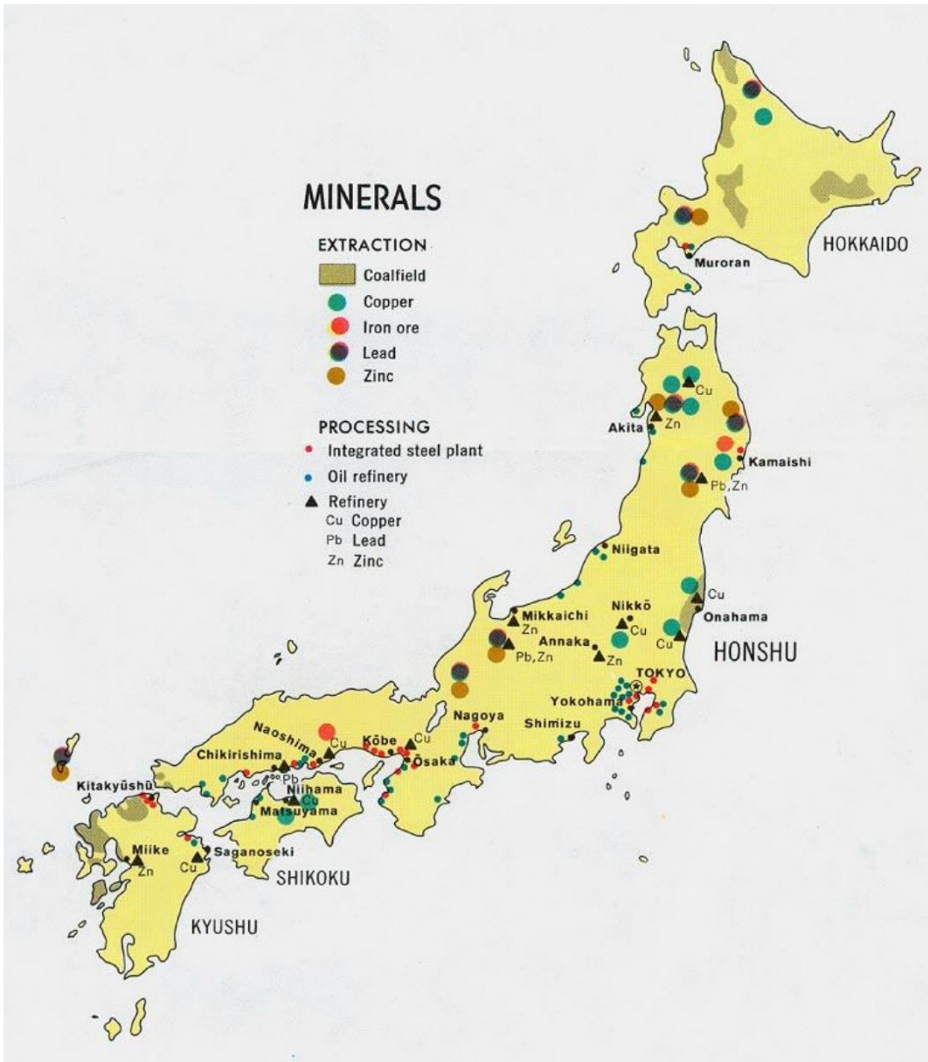


Figure 2. Abandoned and active mines in Japan; see the lead mine in Kitakyūshū in northern Kyushu where lead poisoned families of samurai were excavated (International Committee on Mine Closures, 2008)

Rome is not the only empire in history whose elite suffered from lead poisoning. Much more recently, Japan's Edo period, lasting from 1603 until 1867, was administered by a series of shōguns who oversaw feudal lords and the lords' samurai (Kessler, 2010). In Kokura, modern day city of Kitakyushu, researchers from the University of Occupational and Environmental Health in Kitakyushu excavated rib bones of 70 samurai men, their wives and children buried in clay pots at the local Zen monastery (Nakashima, 2010). Atomic absorption and soft X-ray roentgenograms were used to quantify how much lead was present in the families' skeletal remains. In children under three, scientists detected “a median level of 1,241 micrograms of lead per gram of dry bone” (Nakashima, 2010). “That’s more than 120 times the level thought to cause neurological and behavioral problems today and as much as 50 times higher than levels the team found in samurai adults” (Kessler, 2010). Because women also exhibited higher levels of lead than the men, the researchers hypothesize that the “lead white” face make-up popularized by geisha and theater was absorbed by nursing infants of women wealthy enough to afford the luxury.

Figure 3. Manuscript scroll of gold and silver mining in Sashuu, Japan (National Museum of Nature and Science, 2023)

Mining had long been encouraged by the Japanese government (National Museum of Nature and Science, 2023). Even in the late Middle Ages, Marco Polo called Japan, “the land of gold.” One of the ores well represented in the volcanic islands of Japan is deposits is galena. Found in igneous and metamorphic rock, galena contains ~86% lead as well as arsenic, tin, and mercury (Makra, 2019). Silver-bearing, *argentiferous,* galena is the primary commercial source of silver globally (Makra, 2019).

Several innovations in mining techniques coincided with the Edo shōgunate including new methods of surveying, mining, and smelting. One smelting technique imported from China around this time was the haifuki-ho cupellation method for improving silver yield from ore such as galena (UNESCO, 2010). It is a two-step process where lead and silver are alloyed together and the silver extracted at high temperatures. Although lead was necessary as an industrial ingredient, the most prominent mining records in Edo Japan have been for gold and silver. In the 17th century, Japan produced nearly twenty percent of the world’s gold (Hackett, 2023). The wealth and technology resulting from extensive gold and silver mining would have supported commercial consumption of lead.

In 1621, while Edo Japan was producing twenty percent of the world’s gold, European settlers Virginia began mining for lead (Lewis, 1985). It is likely that American

Indians had already developed extraction and smelting techniques (Keyes, 1912). Dating was limited at the time of publication in 1912, but Keyes cites leaden objects in tumuli of the Mound-builders and lead-inlaid pipes by the Sioux likely a practice older than European documentation. In 1659, Mascoutin Indians of the Mississippi River Valley introduced European settlers to “ample” mounds of lead in the large geological field of what is now Iowa, Wisconsin, and Illinois. A Jesuit priest recorded evidence of mining on the Upper Mississippi as early as 1687, and fur traders on “a sharp lookout for minerals suitable for moulding into bullets” would often be shown suitable existing sources by locals.

Lead bullets would feature prominently in the Civil War, and the expanding frontier created a new market for exterior paints as folks built homes and farms (EDF, 1992). In the 1910s and 1920s, lead paint would become the dominant material for the walls of home interiors, in part because of its durability in the face of washing, something that was more greatly encouraged because of the Spanish influenza that ravaged 1918 resulting more than 100,000,000 deaths (EDF, 1992). While “crazy as a painter” had been an ancient phrase referring to master painters’ use of lead white and subsequent mental instability (Lewis, 1985), the hazards of lead would gain nationwide notoriety through a more contemporary miracle of science.

Three hundred years after the first European operated lead mines opened, Charles Kettering, Thomas Midgeley, and Thomas Boyd would change the distribution of lead in the United States by orders of magnitude. Three engineers for General Motors, they “reported tremendous success” using tetraethyl lead as an anti-knock additive to gasoline in December 1921 (Lewis, 1985). This application of organic lead created conditions to develop higher powered engines that proved essential for U.S. success in World War II and economic dominance of the automotive market through the 1970s.

Although indisputably beneficial, the legacy is overwhelmingly one of problems. One of the inventors, Midgeley, required convalescence leave in 1923 after experimenting with a concentrated liquid form of tetraethyl lead. In 1924, fifteen GM employees in New Jersey and Ohio suffered “terrifying” deterioration of mental health before succumbing to lead poisoning. Prompted by the deaths, then Surgeon General Hugh Cumming halted the sale of leaded gasoline in 1925. Over seven months, deemed “not sufficient” by the investigatory panel, they were unable to produce scientific evidence of the toxic effects of lead in their human guinea pigs but provided this prescient quote,

> “…it may constitute a menace to the health of the general public after prolonged use or under conditions not now foreseen.... The vast increase in the number of automobiles throughout the country makes the study of all such questions a matter of real importance from the standpoint of public health."

When reflected across society, the consequences of tetraethyl lead are devastating, expensive, and dangerous. "BLLs greater than 5 µg/dL were nearly universal (>90%) among those born 1951 to 1980" (McFarland, 2021). By estimating childhood blood lead levels and correlated IQ loss, McFarland's team from the Florida State University calculated,

> "The average lead-linked loss in cognitive ability was 2.6 IQ points per person [in the U.S.] as of 2015. This amounted to a total loss of 824,097,690 IQ points, disproportionately endured by those born between 1951 and 1980."

Although the methodology is largely statistical estimation, it is likely the several million children who were directly exposed to elevated blood lead levels experienced decreases in IQ and ability to concentrate. This has been correlated to reduced academic performance on the SAT (Figure 4). Another correlation to childhood lead poisoning was violent crime (Reyes, 2008). A 2022 meta-analysis by Higney et al. correlated homicide records, violent crime, and elevated blood lead levels from the United States and seven European countries (Figure 5), suggesting about 5-20% of the decline could be statistically attributed to lead poisoning (Higney, 2022).

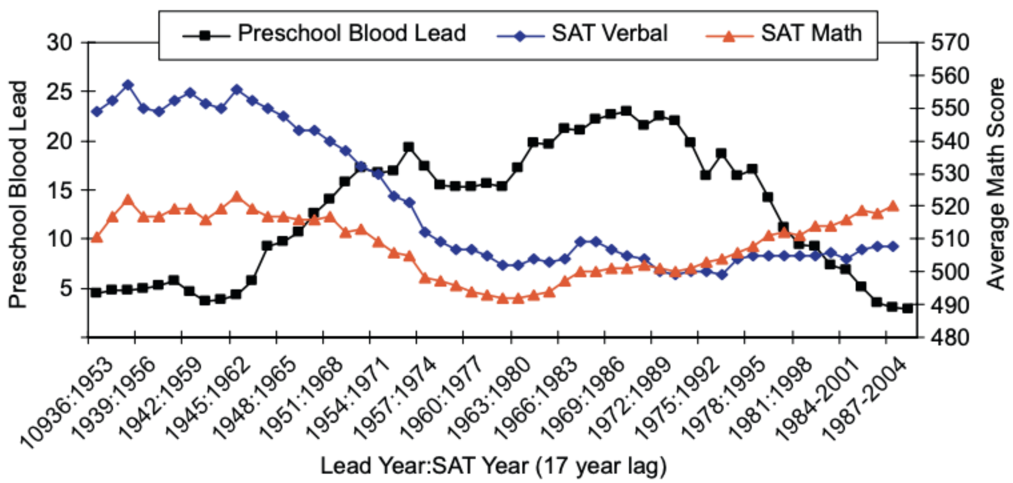


Figure 4. Preschool blood lead versus SAT math and verbal scores with 17-year lag (Nevin, 2008)

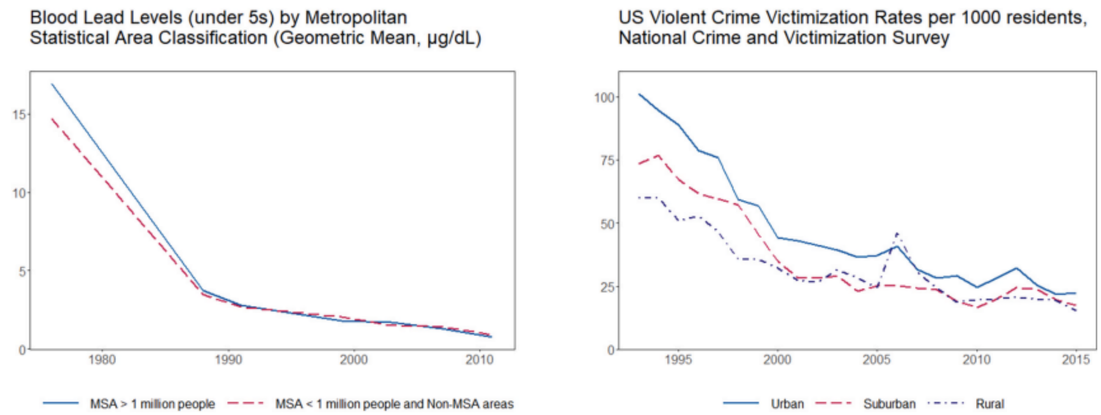


Figure 5. Correlation of decrease in blood lead levels to decrease in violent crime (Higney, 2022)

Reducing the threat of lead poisoning through air pollution was a tremendous success of policy and technological intervention, but the impact of lead paint in homes has been more difficult to remediate. Removing lead paint is an expensive and involved project that many homeowners cannot afford and landlords are hesitant to undertake (Rosner & Markowitz, 2016). Enforcement is difficult; staffing a team of specialized home lead inspectors is costly and untenable for public health departments with limited budgets. Tenants are often ignorant of their rights to a safe home or fear eviction if they file a complaint. For many reasons, including racism, general policy in the U.S. through the 1950s and 70s was not prevention, but identifying children who were already poisoned for the rest of their lives and then responding to clean up their toxic home environment.

Whether or not lead plays a role in the fall of empires, lead poisoning was at least a product of their rise. One of the first identified "industrial diseases" (Gilfillan), elevated lead exposure is both "an environmental disease" and "a disease of lifestyle" (Needleman, 1999). Although lead is a relatively common element, it requires technological effort to concentrate it in such quantities that deleterious exposure is possible. For wealthy ancient Romans, cookware, wine, and water pipes were major sources of exposure. For the families of the more recent Edo shōgunate, it was luxury cosmetics as popularized by the entertainment industry. In the United States, industrial production of leaded paint and gasoline caused several generations of lead poisoning whose legacy remains with us today. There are consequences human development. However, the same capacity of a civilization to produce incredible inventions is also a testament to its capacity for education. With proper education and care, exposure to poisonous lead levels is avoidable.

The Exposure Model of Disease

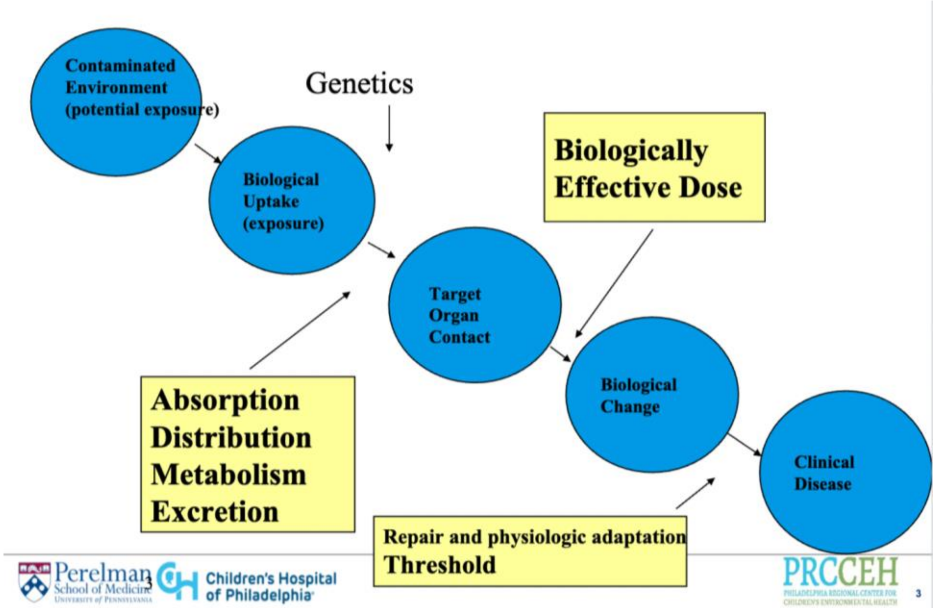


Figure 6. Exposure model of disease (Howarth, 2023b)

Needleman (1999) cites lead poisoning as partially a disease of the environment and partially a disease of lifestyle. The exposure model of disease (Figure 6) organizes these details from the social and life sciences into a stepwise progression from environmental hazard to human crisis. It also generalizes across contaminants. For students at Furness High School, this model will guide their research into historical and contemporary sources of lead concentration, how young children are exposed, why they are particularly vulnerable, and the biological and social consequences of growing up with this toxin in their systems.

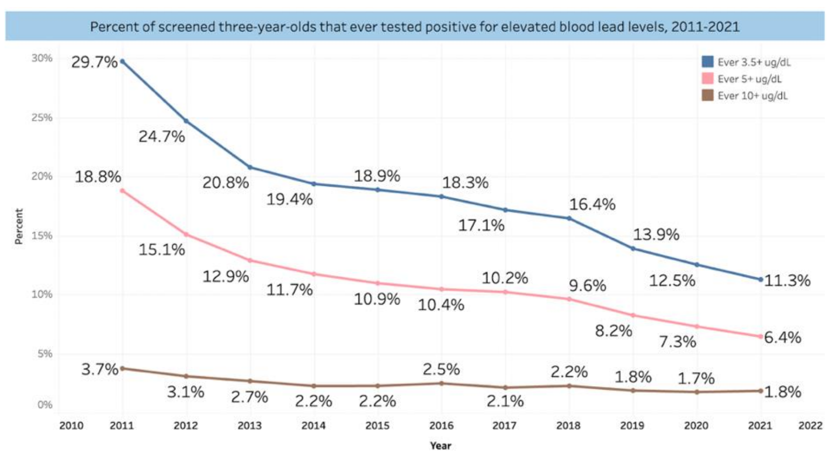
Contaminated Environments

There are many sources of increased lead exposure. The most famous contemporary tragedy in Flint, Michigan caused nearly 100,000 residents to be exposed to elevated lead levels through poor management of municipal water (CDC, 2023). In April 2014, the city switched its water source from the Detroit water supply to the Flint River, in part as a money saving option (Holden, Fonger, & Glenza, 2019). The new water was more corrosive than the Detroit water source they had previously been using, and it was not appropriately treated, as required by law, to preserve the mineral litharge that served as a protective coating on the lead pipes in the city.

Although contemporary coverage of lead exposure in Flint, Michigan has greatly raised awareness of lead poisoning through contaminated water, ingestion of paint remains the number one source of childhood lead exposure (Nemours, 2023). A 1971

New York Times article cited The New York City Health Department statistic that "93 percent of 2600 reported cases [of lead poisoning] last year could be traced to housing" (Hicks, 1971). Until indoor use of lead paint was banned in 1971, nearly 70% of a can of paint was made of lead pigments (Rosner & Markowitz, 2016). Although the dangers of lead poisoning had been well publicized during the early 1920s in GM tetraethyl lead facilities, it was not until December 1970 that the Ryan-Kennedy Bill or, the Lead Based Poisoning Prevention Act, was passed and signed into law by Richard Nixon in 1971. Originally limiting indoor lead paint composition to less than one percent lead pigments, the bill was revised twice, and in 1977, the limit of 0.06% lead is the federal standard that applies until today.

Philadelphia has additional sources of environmental lead contamination. With 36 smelteries within city limits, Philadelphia had the highest number of smelting cites in any U.S. city (ASDTR, 2017). This increases the risk of exposure via soil from legacy pollution from lead smelteries and ammunition in Philadelphia. Philadelphia is also an old city. More than half of its housing stock was built before 1950, well before the ban in indoor paint in the 1970s (Tooher, 2014).



Source: Pennsylvania Department of Health.

Figure 7. Rates of elevated blood lead levels in Philadelphia three-year-olds tested between 2011-2021 (Philadelphia Department of Public Health, 2022).

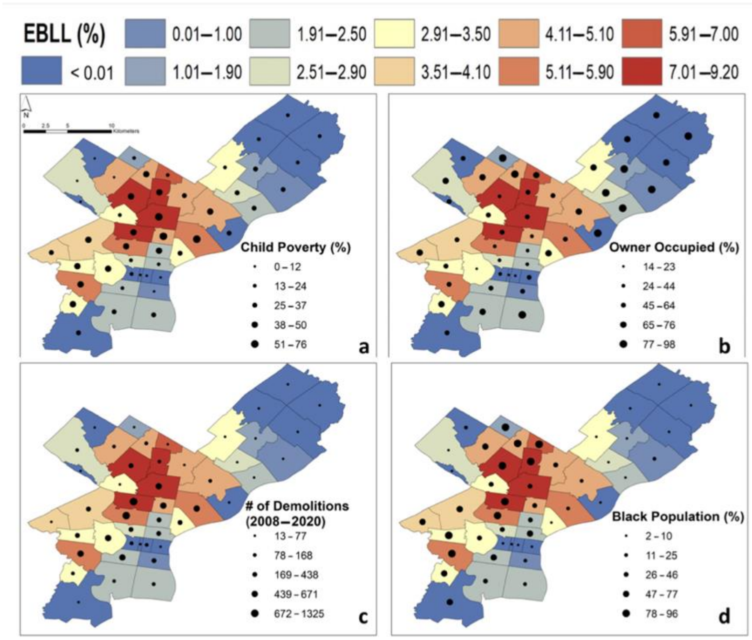


Figure 8. Bivariate plot of elevated blood lead levels against child poverty, number of owner-occupied homes, demolitions, and Black population (O'Shea et al., 2021).

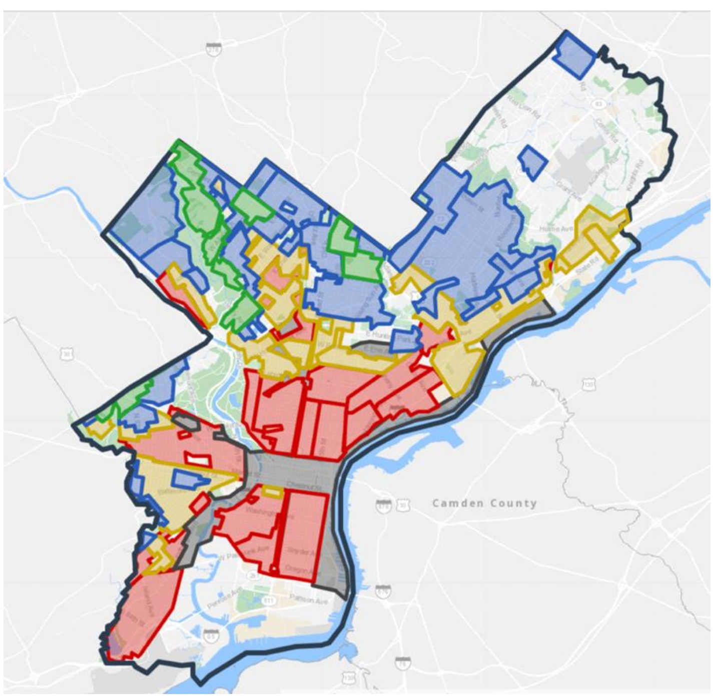


Figure 9. Digitized map of 1937 Assessment Grades for the Homeowners' Loan Corporation in Philadelphia (Philadelphia Office of the Controller, 2020).

In the United States, it is not the elites or their children who suffer most from lead poisoning. A 2017 article for *Clinical Pediatric Emergency Medicine* estimated that 2.5% of all American children under six years old had blood lead levels (BLL) higher than the then-recommended 5µg/dl (Hauptman et al., 2017). During that same year, children tested in Philadelphia were four times more likely to have an equivalent BLL (Figure 7).

Despite a half-decade of improvement and a new CDC's recommended threshold of 3.5µg/dl, more than 10% of our city's three-year-olds tested for lead still have unacceptably rates of exposure (Figure 7). Some of the reasons for this are specific to Philadelphia, including its age, industrial history, relatively high rates of homeownership, racist practices like redlining and gentrification, and the economic challenges of being the poorest major city in America (Unger Ballie, 2021).

These features overlap to unequally distribute risk within Philadelphia. When elevated blood lead levels (eBLL) are mapped against other demographic factors, there are strong correlations for zip codes with high rates of childhood poverty, high percentages of owner occupied housing, the number of demolitions in an area, and the percentage of Black residents (Figure 8). There are nine zip codes in particular where children are twice as likely to have elevated BLL than the rest of the city (Leonard, 2022). Comparing the high risk zip codes shown in red in Figure 2. against the city's historical "red-lining" map in Figure 9 shows considerable overlap. The people who continue to be most negatively impacted by America systemic racism are Black Americans. Racist history blends indefinitely into a racist present.

Biological Uptake

Lead enters the body through three ways. It can be ingested, inhaled, or absorbed through the skin (Agency for Toxic Substances and Disease Registry, 2023). When it comes to toxic levels of exposure through ingestion, about 1% of cases involve ingestion through water and about 99% are cases of ingestion of lead paint (Lanphear, 2016). Both behaviorally and physically, children are especially vulnerable to this toxic lead exposure. One major contribution to behavioral lead exposure is because lead tastes sweet. When a young child starts to crawl in a home that has lead paint in the walls or flaking along window sills, they are incredibly active, able to fit into small, unsupervised spaces, and are strongly motivated to ingest things that taste like candy. The positive feedback of discovering something delicious reinforces the behavior and can lead to greater exposure over time.

Children's bodies are also very different from adults. Smaller bodies mean higher ratios of lead per unit body mass for the same amount of ingestion. Gastrointestinal uptake of lead is also higher in children than in adults (Rădulescu & Lundgren, 2019). Once ingested, infants and toddlers have greater metabolic rates, increasing distribution of lead through the body. These relatively higher concentrations are further compounded by kidneys not effectively concentrating urine until twelve to eighteen months of age, leading to less effective excretion of lead (Figure 10).

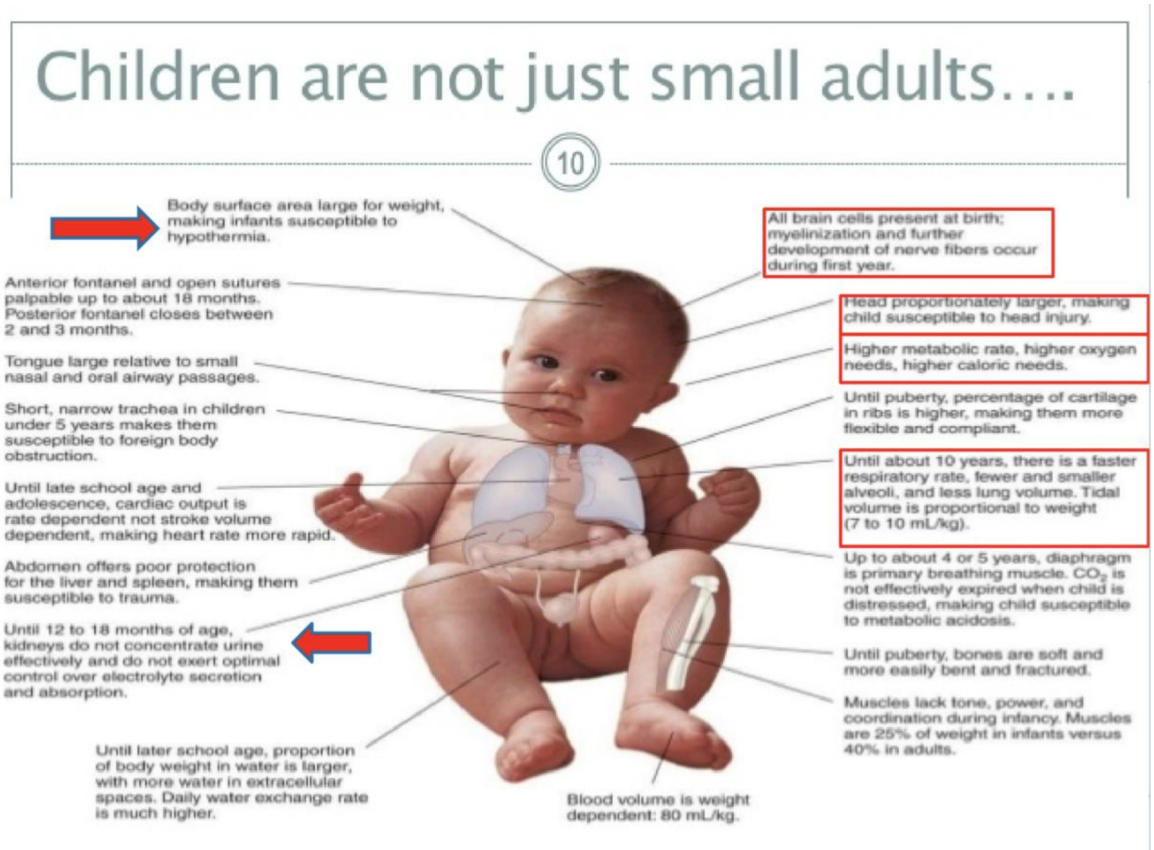


Figure 10. Features of children that make them more vulnerable to lead exposure (Lanphear, 2016)

Target Organ Contact

Once it has entered the body, lead affects all organ systems (Lanphear, 2016). Some of the earliest models of how lead reaches those organs were designed in 1973 by Rabinowitz et al. who offered a three-part “compartmentalization model” for rates of lead diffusion and excretion. In this rudimentary model based on ingestion of stable lead isotopes, one “compartment” of lead concentration in the body is blood and the soft tissues that are in rapid exchange with blood. These distribute lead throughout the body and are subject to excretion through urine. The second compartment is soft tissues, which absorb lead through the blood and excrete it through hair, sweat, saliva, and fingernails. The third compartment is the skeleton, which absorbs lead via exposure to blood or some soft tissues and is where the majority of bodily lead is concentrated. It had no mechanism of excretion observed in the isotope trials over 240 days (1973).

This 1973 model did very little to explain lead's particular neurotoxicity or how its calcium-like behavior induced uptake in various organ systems. A number of models were proposed to fill those gaps, including a widely-used 20-compartment system in 1993 by Leggett et al. In 2019, a biophysical model by Rădulescu and Lundgren updated the three-compartment model with more granularity and several decades of additional research, especially reflecting more recent trends toward lower blood lead levels in the general population. What makes this model particularly relevant is its broad capacity to project age dependent differences in lead exposure. Some of these factors included in the model are developmental differences in metabolism and pharmacokinetics, as well as behavioral norms that can lead to greater lead ingestion based on age.

While many aspects of the older models are retained, including the simplicity of Rabinowitz' limited compartment system, the differences are notable. The majority of bodily lead being retained in mineralized tissues remains, but an age-dependent model reflects that because children have a faster rate of turn-over in bone, only 70% of lead in children is found in teeth and bones compared to ~95% of lead in adult tissues. In both adults and children, this mineralized tissue can act as a source of lead into the blood stream even after the environmental lead exposure has been removed.

Biological Change

While lead has no known biological function in the human body (ATSDR, 2023), calcium is essential. Lead competes with calcium for absorption (Rădulescu & Lundgren, 2019). This suggests an explanation for why lead is maintained in the body most readily through the bones. It also explains its particular neurotoxicity. Lead can block calcium as an agent of neurological signaling, resulting in a decrease in the amount of neurotransmitters released and ultimately weaker signals (Gearing, 2016). The presence of lead can also induce aberrant signaling where no calcium is present (Gearing, 2016). Causally still under investigation, elevated lead exposure in children was correlated to reduced size of prefrontal cortex as young adults, the area of the brain responsible for rational decision making (Gearing, 2016).

Calcium is an essential component in many of the electrical signals of the human body and is thus also essential in the cardiovascular system. One of the most common signals induced by calcium is this signal is tightening of the vascular system to increase blood pressure (Gearing, 2016). Similar to the brain, the presence of lead can induce this signal in the absence of calcium, creating conditions of on-going high blood pressure that can weaken blood vessels and increase risk of heart attack and stroke (Gearing, 2016).

Clinical Disease

For the individual, lead poisoning is toxic to every body system and what constitutes a biologically effective dose is not directly correlated to a particular blood lead level

(Agency for Toxic Substances and Disease Registry, 2023). This means that symptoms and thresholds of elevated lead exposure are wide-ranging. For a particular body with low levels of exposure, consequences include decreased cognitive capacity, fatigue, and discomfort (ATSDR, 2023). For moderate exposure, symptoms can include abdominal pain, headaches, tremors, and vomiting, with the most severe exposures inducing potentially fatal seizures (ATSDR, 2023).

Teaching Strategies

Place-Based Learning

An essential component of Project-Based Learning is that student work should have real world application. By utilizing a place-based approach to studying environmental hazards, it increases personal investment in the scientific skills and results (Minero, 2019). "Why are Philadelphia and my school full of lead and what can I do about it?" is potentially more compelling investigation than studying Love Canal or toxic exposures in the abstract.

Knowles Engineering and Design for Social Justice

Developed by the Knowles Teaching Initiative for high-impact, culturally relevant lessons, an engineering design process is a professional technique for exploring a problem, assigning constraints and criteria to measure and rank outcomes, then prototyping, testing, and communicating efficacy and trade-offs of proposed solutions. These steps allow significant overlap for the Next Generation Science Standards science and engineering practices. All eight of the identified skills of STEM professionals can be incorporated with intentional design, but these four are always achieved by proper implementation of the process:

- Asking questions and defining problems
- Planning and carrying out investigations
- Analyzing and interpreting data
- Obtaining, evaluating, and communicating information

While this process can be applied to almost any academic material, research shows that self-identifying as an engineer or scientist is more likely when young people are positioned as experts in the problems of their own lives, and the skills of these professions are taught as techniques for empowerment and change. Knowles provides strategies for connecting the engineering protocol to student driven social justice. Framed in four steps from purely engineering design to a fully student-driven project to change their world, the implementers do not encourage educators to aim for a fully student-driven project every time. It is important that young people experience many different kinds of projects as scaffolding for more involved ones.

Although my school's zip code is not one of those most severely impacted by lead poisoning, our sinks have the red spray-painted hazard, "Do not drink from this sink," and a previous year's students found hot-red positive for lead on the drain of our filtered lead fountains. There are still 60,000 lead connection lines in Philadelphia (Jaramillo, 2017). Students can use observation and investigation to learn if their homes are one of those impacted. Many of my students are immigrants or children of immigrants. How aware are they of potential risks and what can be done to increase awareness? Because my students know, love, and care for people who are at most at risk for lead poisoning, it provides a personal and emotional context to science skills and applies them in a way that could make real change in their lives.

Classroom Activities

Keystone Biology Anchor BIO.B.4.2.4 Describe how ecosystems change in response to natural and human disturbances (e.g., climate changes, introduction of nonnative species, pollution, fires).

PA STEELS Life Science Standards 3.1.9-12.N Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.

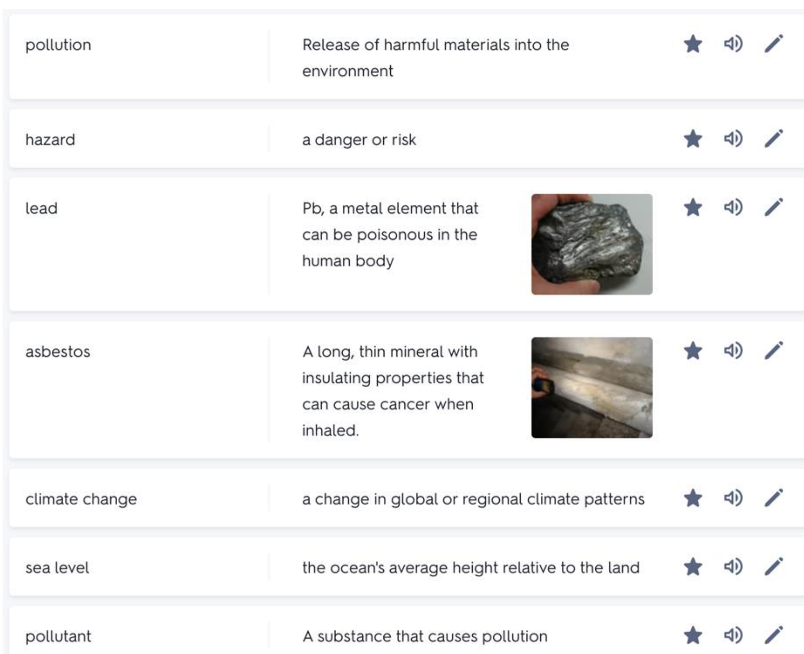


Figure 11. Selection of Quizlet.com vocabulary words for documentary project

Gamification of Vocabulary

Explicit academic vocabulary will be studied by repeated, "gamified" exposure through Quizlet.com (Figure 11.). Although a basic program is available for free, I pay ~$32 annually for the premium version that allows additional game options and unlimited study modes for students. When conducting the whole class activity, I use a SMARTboard to login to my district-associated account and select the “Environmental Hazards Documentary” study set before students arrive to class. As students enter the classroom, they are prompted to login to “Quizlet.live” using the code projected on the board, which allows them to access digital flashcards with vocabulary and definitions. When the game starts, students match either the definition to the word or vis versa. The fastest student is rewarded with candy or points from our school’s Positive Behavior Intervention System. The fasted student is also removed from play so that other students have an opportunity to win. Memorization of this vocabulary is assessed in weekly quizzes in which the definition is projected onto the board and students must write down the accompanying word from a word bank they copy at the beginning of class.

QTEL Jigsaw Reading

Reading and using the vocabulary in context is achieved using the Quality Teaching for English Learners (QTEL) technique of jigsaw reading. In this QTEL approach, each small group of students receive one of five to seven paragraphs of text from four *Philadelphia Inquirer* articles in the “Toxic City” investigation series. They receive a set of sentence starters to analyze the text (see Appendix, “Sentence Starters: Claim, Evidence, Reasoning”). Teachers may customize which analysis formats are used for a given article, graph, or data set. Once analyzed in small groups, students transition to new groups to share their article expertise and compare viewpoints into a more holistic understanding, which is then reviewed back in the original small groups.

Multimedia Video Project

The final research projected is implemented as a multimedia video in partnership with WHYY. Citing background information from their text analysis, students will choose groups in alignment to personal interests. For example, students interested in biomedical sciences may elect to study biological changes as a result of lead while students interested in law or history can research the historical threads that result in disparate lead concentrations across Philadelphia. Their research is set up in a three-part narrative, “What is the problem? How did it happen? What can we do?” Depending on the ability level and interests of students, additional information will be provided in teacher curated readings as well as student free-choice of resources as long as they are cited.

In the first unit, students introduce and describe the issue. Some examples maybe include the medical symptoms of lead poisoning, where and whom in Philadelphia experiences greater rates of lead poisoning, what physiology and behaviors do children have that make them more vulnerable? This part of the project is accompanied by an introduction to B-footage using an interview with Furness High School Principal Dan Peou on NBC national news describing the abhorrent conditions of our building (which were remediated after the attention in June 2021). As students in the segment describe what is wrong with the building, still images of the problems are slowly panned over for illustrative connection between word and image. While researching the text of their project, students write keywords they would like to search to visually demonstrate their point in pairing with the text.

The second part asks students to think use the NGSS Cross-Cutting Concept of "Cause and Effect" to explain several steps in the unfolding of their problem. Again based on which interest topics are selected, students will received curated texts and be asked to verbally connect ideas on a timeline of history. Anti-Black racism and globalized capitalism led to enslavement of people in Africa and post-"Emancipation" codification of that racism into Federal Housing Authority lending policies known as red-lining. That policy led to disinvestment in housing infrastructure at the same time lead based paints were the dominant interior design choice. At the time children are just learning to walk and explore, they are able to escape supervision into small spaces and like to learn by putting things in their mouths. This is the most injurious time to be exposed to a heavy metal like lead.

The final aspect of the project is to learn about regulation and remediation and to brainstorm where the action of 9th graders may be able to make a difference. Should students approach City Council or should they make informative pamphlets for their own communities, translated into their home languages? When each of their video projects are combined, we will invite local officials to a screening in our historic auditorium with a Q&A of student volunteers if possible.

Resources

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Appendix

Keystone Biology Anchor BIO.B.4.2.4 Describe how ecosystems change in response to natural and human disturbances (e.g., climate changes, introduction of nonnative species, pollution, fires).

PA STEELS Life Science Standards 3.1.9-12.N Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.

By researching the different stages of how environmental contaminants progress from pollution to disease stage, students will learn how to design preventative measures at each step that reduce the risk of exposure through changes in the environment, behavior, and awareness.

Quizlet.com “Environmental Hazards Documentary” vocabulary link: https://quizlet.com/738278702/environmental-hazards-documentary-flash-cards/?i=2ex4zj&x=1jqt

NBC Interview with Dan Peou, https://www.nbcnews.com/now/video/philadelphia-principal-warns-of-unsafe-building-conditions-says-school-looks-like-third-world-country-114193477732

Sentence Starters:

Claim, Evidence, Reasoning

CLAIM: answers the question

- I observed ______________ when ____________.
- I compared ______________ and ____________ and found that _____________.
- I noticed ________, when ________.
- The effect of __________ on ____________ is ____________.

EVIDENCE: scientific data that supports the claim

○ Data are observations or measurements OR results from an experiment.

○ Use specific examples, numbers, and data table information

- In the data _____________.
- The evidence I use to support _____________ is _______________.
- I believe _____________ (statement) because _____________ (justification).
- I know that _____________ is _____________ because _____________.
- Based on _____________ , I think _____________ .
- Based upon _____________ , my hypothesis is _____________.

REASONING: why the evidence supports the claim, connects the evidence to a scientific rule

- Based on the evidence, we must conclude____________ because___________.
- The most logical conclusion we can draw from this evidence is that________ because________.
- These facts work together to build a case that__________ because__________.
- All of this proves that__________ because _____________.
- The reason I believe _____________ is _____________ .

Group Members:

Research Guide:
Lead in Philadelphia
(2023 - 2024)

Highlight one aspect of lead poisoning to study:

History of contamination	How lead gets into children, people	Lead in the body and disease	Laws and remediation

Part One: What is the problem?

	Define the problem.	Why is it a problem?	Where in Philadelphia does it happen most frequently?
Text			
B-footage			

Part Two: How did it happen?

	What are some of the earliest records of the issue?	Explain step-by-step the factors in your issue.	How is it expected to change in the future? Why?
Text			
B-footage			

Part Three: What can we do?

	How can people protect themselves from lead?	What can people do to prevent lead poisoning for others or make it less severe?	Student Reflection/Proposals
Text			
B-footage			

Quotes from existing articles:

Quote	Article Link

Questions for experts:

Quote	Article Link

Questions for someone who personally experience(s) this problem:

Quote	Article Link

SCRIPT

FIRST SPEAKER:

SECOND SPEAKER:

THIRD SPEAKER: