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Article

Emergy Evaluation of Formal Education in the United States: 1870 to 2011 †

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Abstract: We evaluated the education system of the United States from 1870 to 2011 using emergy methods. The system was partitioned into three subsystems (elementary, secondary and college/university education) and the emergy inputs required to support each subsystem were determined for every year over the period of analysis. We calculated the emergy required to produce an individual with a given number of years of education by summing over the years of support needed to attain that level of education. In 1983, the emergy per individual ranged from 8.63E+16 semj/ind. for a pre-school student to 165.9E+16 semj/ind. for a Ph.D. with 2 years of postdoctoral experience. The emergy of teaching and learning per hour spent in this process was calculated as the sum of the emergy delivered by the education and experience of the teachers and the emergy brought to the process of learning by the students. The emergy of teaching and learning was about an order of magnitude larger than the annual emergy supporting the U.S. education system (*i.e.*, the emergy inflows provided by the environment, energy and materials, teachers, entering students, goods and services). The implication is that teaching and learning is a higher order social process related to the development and maintenance of the national information cycle. Also, the results imply that there is a 10-fold return on the emergy invested in operating the education system of the United States.

Keywords: emergy evaluation; formal education; teaching and learning; United States

1. Introduction

Emergy is a universal accounting quantity, which was derived by Odum [1] (Chapter 3) from the first and second laws of thermodynamics and Lotka's maximum power principle [2–4]. In this paper, the evaluation of the formal education system of the United States was carried out by first determining the available energy, material, and information inputs used up both directly and indirectly to make a product or service within the U.S. education system in their native units (e.g., joules, grams, *etc.*) and then converting these quantities to solar emjoules (semj) by multiplying by the appropriate UEV or emergy per unit value (e.g., semj/J, semj/g, semj/$). The emergy unit is the solar emjoule, which is a solar equivalent joule that has been used in the past as contrasted with a joule of available energy within a product or service, which is potential energy that can be used in the present.

Odum characterized human beings as Earth's information processors [1]. He pointed out that humans arose late in the evolutionary process of the Earth and that they have highly developed information processing organs and use social mechanisms for group information processing, e.g., art, music, sports, *etc*. Perhaps because of their facility in developing and using information, as well as, the opening of vast fossil energy resources for use in supporting human activities in the Industrial Age, human beings have come to control many of the living and nonliving system operations on the surface of the Earth. For this reason, the world has become a human-dominated system [5–7], in which human agency accounts for and controls the majority of many material and energy flows [8,9] of the biogeosphere. Because of the magnitudes of anthropic effects on the environment and anthropic demands for environmental resources to support economic and social activities, discovering more accurate methods for valuing the contributions of the environment to human wellbeing has become an imperative for ecological-economic research.

Past research has shown that the environmental, economic, and social costs and benefits of alternative economic and environmental policies can be quantified in equivalent terms based on the relative ability of various individuals, products and services to perform work in a system [1,10–13]. These equivalent work potentials are measured by emergy, which is quantified as the available energy of one kind, e.g., solar joules, that is used-up in the process of making a product or service. In this paper, we used the standard calculation methods for quantifying emergy (Odum 1996) [1] to estimate the emergy delivered to the system in the knowledgeable work of people, which underlies all kinds of human service; and which, at present, is most often measured in terms of money. The end result of determining the emergy required to produce individuals with varying amounts of knowledge (*i.e.*, as measured in this study by an individual's education) is that we will be able to estimate the emergy potentially delivered to a national system, e.g., the United States, by individuals employed in the workforce. When this information is applied in an emergy evaluation, it will result in more accurately quantifying the relative contributions of the work of people and the work of the environment in operating a system such as the United States.

An assumption underlying the potential usefulness of the results reported in this paper is that the work performed by individuals in carrying out economic and social activities is primarily a function of their knowledge and experience. Thus, we assume that the knowledgeable work done by people employed in social and economic activities underlies all kinds of human service. The work done by people is dependent on a storage of information (*i.e*., their knowledge and experience), which requires an information cycle [1,14] for its development and maintenance. Because of the operation of the second law of thermodynamics, which causes the degradation of information carriers and the pressure for innovation caused by evolutionary competition, all living systems include an information cycle, which is needed to maintain the information controlling the structure and function of the system and to prevail in competition with other systems. The information maintenance cycle includes the following processes: depreciation, extraction, copying, dispersion of copies, operation, testing in use and selection [1] (Figure 12.2). As a result, human knowledge and experience have unique properties that require us to consider the role of time in their creation. First, the knowledge base of an individual or of a nation cannot be generated in the course of a single year, which is the standard temporal unit used for most emergy analyses. In general, individuals go through many years of school or other training, while they accumulate enough knowledge to profitably enter the workforce. In a similar manner, the stored knowledge and experience of the people of a nation cannot be generated quickly. Even if the information has been derived earlier in another time and location, it still requires at least a generation for those trained in the various fields of knowledge to reach their full potential and to train the next generation of students to establish a more advanced level of knowledge in the system.

A second unique aspect of human knowledge is that it is not diminished by use; in fact, it increases as individuals learn more about their fields through the application of what they have learned. Thus, the information that individual workers contribute grows throughout their career and as a result the emergy of their knowledge increases as does the transformity of their work, *i.e*., the emergy delivered per joule of metabolic work. The storage of knowledge and experience of a people is diminished, ultimately, by death. In addition, unemployment and sickness diminish its application in carrying out economic and social activities in any given year. Retirement changes the way that the knowledge of an individual is used by society and, sadly, aging begins to erode the knowledge of many.

The work of people with varying levels of education and experience plays a fundamental role in determining the kinds of economic and social activities that can be carried out within a system. The emergy required for much, but not all, of the information stored in human knowledge can be evaluated through an analysis of the formal education system of a nation. In this study, we evaluated the formal education system of the United States from 1870 to 2011 using emergy methods [1,15] to provide information critical for establishing the equivalence between the emergy contributed to a system by the work of people and the emergy contributed to the system by the work of the environment. This study is also the second step on a research path to produce an integrated method of environmental accounting based on a combined emergy-money unit as defined in [16].

In this study, we assumed that a person is paid for the information (knowledge and experience) that they deliver in their work, and that the emergy equivalent of this information can be calculated by summing the emergy required for the education of an individual up to a particular time. First, we determined the emergy required annually to support each level of education, *i.e.*, elementary, secondary, and college/university. Second, we calculated the emergy required to train an individual up to the various levels of education of interest to us, *i.e.*, pre-school through the professional and doctoral degrees. This was accomplished by summing the emergy required to support a student each year, over the years that the student spent in school up to the time when they graduate or dropout. Finally, we estimated the emergy required for the process of teaching and learning at elementary, secondary and college/university levels, *i.e.*, the cumulative emergy of the students and teachers brought to the classroom. The activity of teaching and learning was found to be a higher order social process dependent on the emergy required for the transfer and reproduction of information. We provided a table of Unit Emergy Values (UEVs) for individuals with various levels of education from 1870 to 2011 for use in subsequent emergy analyses.

2. Prior Methods and Studies Related to the Evaluation of the Emergy of Human Service

Odum (1996) [1] applied the term "human service" to a broad spectrum of human activities including the emergy delivered by different levels of education and experience, emergy accounting for schools and universities, the emergy of teaching and learning, the emergy of television and information transfer (e.g., the internet), and the emergy in culture. In this study we consider the first three aspects of human service listed above. In general, human service of all kinds is often a high quality (*i.e.*, high transformity or high emergy per unit available energy) feedback, interacting with lower quality material and energy resources to make value added products of intermediate transformity.

Our concern in this paper is primarily with ways of quantifying the work done by individuals with various amounts of knowledge and experience, *i.e.*, in this case, with varying levels of education. For example, money, *i.e.*, income and wages, is only paid to people for their work and as a result the emergy of "human service" can be approximated by multiplying the money flow accompanying the work performed in carrying out a given task by the emergy to money ratio of the system within which the work was performed. However, Odum [1] states that this method is only valid when the service is performed by a person with the average level of knowledge and experience found in the system being evaluated. Another method that Odum [1,17,18] used to evaluate the work delivered by people with different amounts of knowledge and experience was to divide the total national emergy flow (or national empower as semj/y) in a given year by the number of people that possessed a given level of education or higher. In this method he calculated the emergy per individual based on the number of people in the population who have attained a given number of years of education. The transformity (semj/J) of an individual's labor was then determined by dividing the annual metabolic energy (J) of an individual into the emergy (semj) of an individual with a given level of knowledge. Odum [1] (p. 232) presents the results of this calculation for the United States in 1983.

Both of these methods of estimating the emergy delivered in the work of people are rough approximations. The commonly used method of multiplying the money flows by the emergy to money ratio essentially uses the information of the money flow to scale the emergy estimate, rather than the process that Odum [1] originally defined, which was to use the emergy flows to scale the money flows in an economy, thereby showing the source of buying power. The second method may be more accurate, because it is based on the emergy flows supporting the national system in a given year. However, it is based on the assumption that the knowledge system of the nation is in steady state and that the current cumulative distribution of people who have attained a given number of years of education can be taken as the output of the education process. This calculation method implies that all the emergy inputs to the nation in a given year and only those inputs are required to produce all the people that have attained a given number of years of education or greater. However, since the data demonstrate that the U.S. national education system has not been in a steady state over the period from 1870 to 2011 and since we show that there is a time requirement for the creation of knowledge, a more accurate method for determining the emergy required for the knowledge and experience delivered by an individual's work may be to analyze the education system required to generate and transfer knowledge.

In an earlier version of this paper, we developed and applied a more accurate method of assessing the emergy of education levels in the U.S. based on evaluation of detailed models of elementary, secondary, and college/university education in the nation from 1870 to 2006 [19]. In this study, we used modeling methods to construct the time series of data needed to evaluate the system. Also, we accessed most of the data from the U.S. Statistical Abstracts 1870 to 2009 [20], which combined with key additional data sources allowed us to calculate and then sum the emergy requirements for each level of education over the time in school to gain a particular degree or level of training. In the present study we have reported, for the first time, five additional years of data (2007 to 2011), which allowed us to examine the effects that the Great Recession of 2008 (GR08) had on the education system of the U.S., and to check and refine our earlier methods and calculations so as to increase the accuracy of the results.

Berquist *et al*. [21] pointed out that a complete approach to evaluating human knowledge must be able to evaluate local traditional and informal knowledge [22,23] as well as formal education. They proposed that the calculation of UEVs for human labor should consider four factors: caloric intake, the quantity and quality of knowledge, how knowledge is transferred between individuals and in the broader society, and the cultural context within which the knowledge is applied. They illustrated this process with a hypothetical calculation of the development and transfer of knowledge of millet farming in a traditional system of subsistence agriculture. However, they state that we [19] believe "that human knowledge is created when individuals carry out economic processes…", rather we would say that human knowledge is applied or in some cases accumulated (e.g., through education) in the system when individuals carry out economic processes. In one sense, the authors of [21] are correct, because knowledge is created when economic processes are carried out to the extent that learning through experience occurs as the work is done. Furthermore our research implies that knowledge is created within the social and cultural context of all education systems (formal, traditional, or informal) supported by the emergy of the resource inputs needed to carry out the process of teaching and learning. Thus, in this study and in [19] we used a similar approach to that put forward in [21] to evaluate formal education in the U.S. However, in our study we assumed that the available energy expended in metabolic work of an individual delivers the emergy of that individual's knowledge and experience to perform a task, for which they have been trained.

Abel's work on expanding the scale of estimates for the transformities of human work [24] established by Odum [1,18] based on education level are relevant to this study. Abel [24] applied Odum's method to quantify the emergy supporting various levels of social organization in the world as a whole. In this way he estimated transformities for a range of individuals from the world's poor to the world's super elites, *i.e.*, the 55 most powerful people in the world. This hypothetical calculation was based on a global emergy inflow of 15.83E+24 semj/y and a world population of 6.11 billion people, allowing for nine levels of transformity from 5.5 billion to 55 individuals with the first level split into two parts, 1 billion poor and 4.5 billion others. Abel [24] argued that the household, not school, might provide a better location for evaluating the production of people. He calculated household emergies in a county, and produced an emergy pyramid or hierarchy using the data. While he did not calculate an associated hierarchy of human transformities, he did calculate one transformity (for the average household) as a demonstration of the method that could be used at every location in the hierarchy.

3. Models of the U.S. Education System and of Teaching and Learning

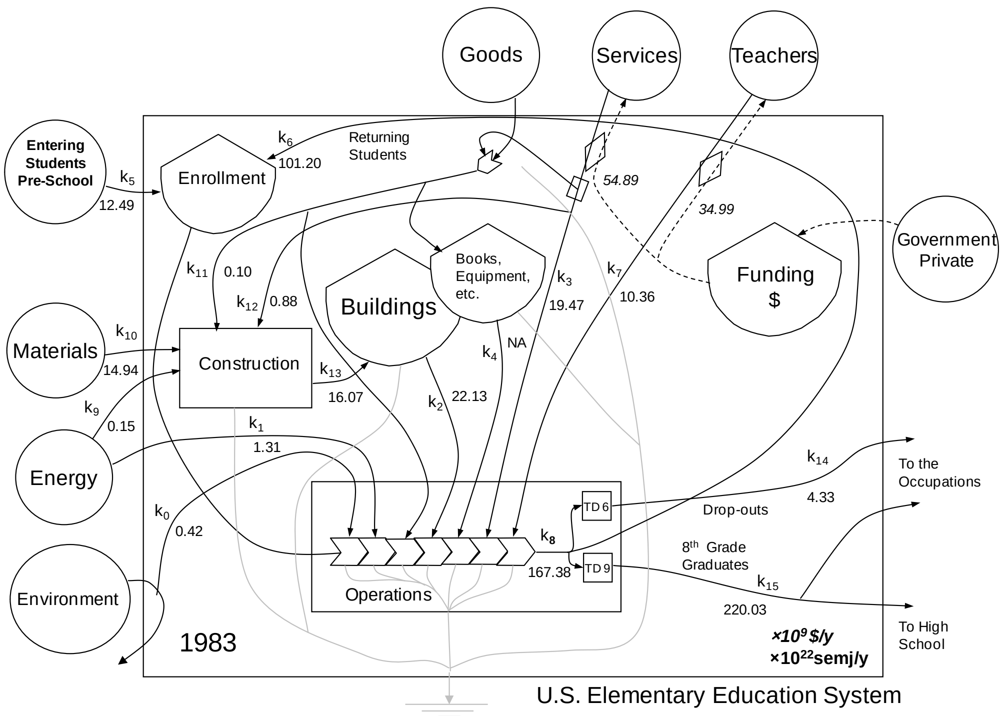
Education covers a portion of Odum's [1,14,18] model of the information cycle. We agree with Abel [25] (Figure 8), who represented formal education within the information cycle model of Odum [1]. In this model [25], formal education covers that part of the information cycle in which information is selected from operating systems through a determination of what is successful within the existing milieu of society and science. Teachers then extract this working information in accordance with their various disciplines into a form that can be communicated to students through the process of teaching and learning, *i.e.*, the reproduction of knowledge or copying. Graduates containing the copied information are then released back into the world once they leave the education system, carrying their part of the shared information to use in operating the system. The university education system plays an additional role in the information cycle, in that part of its work is the creation of new knowledge in the cycle as shown in [1] (Figure 12.1). This aspect of the U.S. education system is not evaluated in this study.

3.1. Model of the U.S. Education System

An Energy Systems Language, (ESL) model [26] of the education system of the United States is presented in Figure 1, where the system is divided into three subsystems: elementary, secondary, and college/university education. Each subsystem has its own inputs and outputs, which are quantified in the figure using values for 1983. We chose 1983 as the year to illustrate our calculations, because this was the year upon which Odum [1] based his initial evaluation of the U.S. education system. Each pathway is also marked with a pathway coefficient, the subscripted letter, k; which in turn is entered as a line item in Table 1, where the definition of the pathway is given along with its value. The letter k with the same subscript is repeated for similar flows in each subsystem. While the model was evaluated for 1983, values for the model output in any year can be found by consulting Appendix B given below.

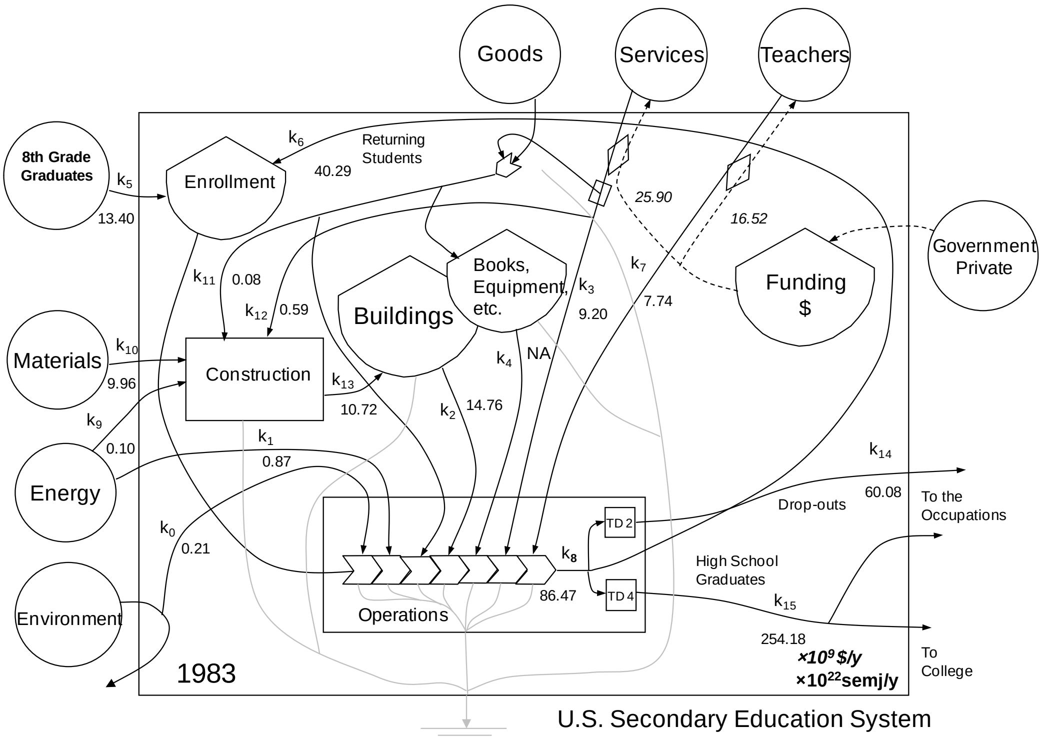
The emergy inputs required to run the U.S. education system at each level are shown as emergy flows from external sources or from internal storages that enter the box marked "Operations" (Figure 1). Sources include the emergy inputs from: the environment, k_0; the energy used to operate the system, k_1; the energy, k_9, and the materials (lumber, paper, chemicals, petroleum products, stone, glass, concrete, primary metal and fabricated metal), k_{10}, used in building construction; the new students enrolling in school, k_5; students returning to school, k_6; the goods used in construction (*i.e.*, machinery except electrical, electrical machinery, instruments and related, misc. manufactured items), k_{11}; the services used in construction, k_{12}; the goods and services used to operate the schools, k_3; libraries and equipment, k_4; and teachers, k_7. The total annual emergy supporting the education carried out within a subsystem is given by the pathway coefficient, k_8. The outputs of the education systems are graduates, k_{15}, and dropouts, k_{14}. College/University (Figure 1c) was evaluated as a combined system with outputs ranging from a two year associate degree, k_{14}; through college graduates, k_{15}; master's degree, k_{16}; 3-year professional degree, k_{17}; to the Ph.D., k_{18}. College dropouts, k_{14}, were assumed to have, on average, an education equivalent to the 2-year degree. The emergy per individual was modeled based on the time that a student remains in school. Thus, the difference between a Ph.D. and an average dropout with two years of college is the emergy required to support the doctoral graduate in the school system for an additional 6 years. Doctoral candidates, who spend more time in school or who complete post-doctoral fellowships, have greater emergy per individual. We also determined the emergy of individuals who had had 2 years of postdoctoral experience and the emergy required for medical doctors (not shown in Figure 1c), who generally spend 4 years in medical school followed by a year internship and an average residency of 4 years. Assuming a 30 year replacement time for school buildings, the depreciation in a given year (for example, k_2 in Figure 1c) represents the contribution of college infrastructure to the emergy required for the education process. Books and equipment are shown as a separate storage for all subsystems, but because of the limited data available, libraries were the only aspect of this storage that we quantified explicitly, and this was done only for colleges/universities. The storage of books and equipment was quantified as part of the general expenditures on services for the other subsystems, and the emergy of the equipment in college buildings was included as a part of overall college services.

Figure 1. An evaluated Energy Systems Language (ESL) [26] diagram of the formal education system of the United States showing three subsystems: (**a**) Elementary education, kindergarten to eighth grade; (**b**) Secondary education, grades 9 to 12; (**c**) College/University education. The values on the diagram are for 1983 and the model pathways are defined in Table 1. Plain text is emergy flow in solar emjoules per year $\times 10^{22}$ (semj/yr) and italics shows annual money flows in nominal dollars $\times 10^9$ (\$/yr).

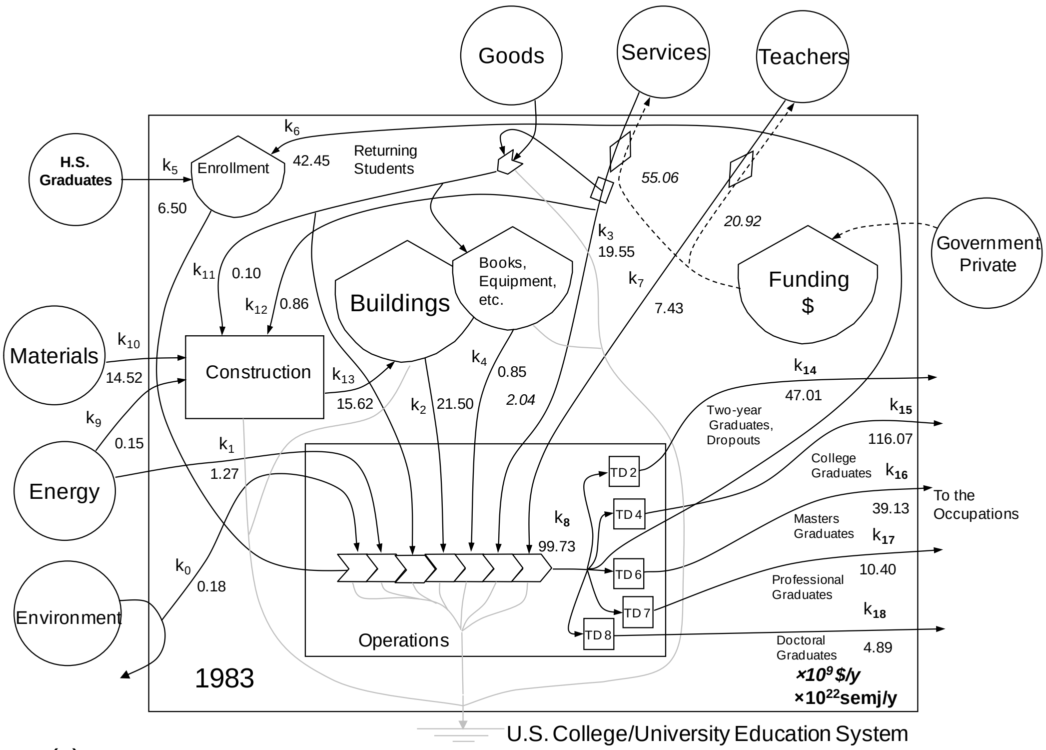


(a)

Figure 1. *Cont.*



(b)



(c)

Table 1. Definition of the pathways in the ESL models of the education subsystems of the United States (Figure 1). Note the emergy of k_0 to k_7 sum to k_8 the annual emergy required for school operation at an education level, the emergy of k_{14} dropouts and k_{15} to k_{18} school completers is the sum of the emergy support over the years spent in school (1983 + all prior years), and k_9 to k_{13} evaluate building construction put in place in that year.

Pathway	Definition of Emergy Flow	Value $\times 10^{22}$ (semj/y)
Elementary Education (Figure 1a)		
k_0	Renewable resources used on the school grounds	0.42
k_1	Consumption of fuel and electricity to run the schools	1.31
k_2	Depreciation of school buildings (0.0333 per year)	22.13
k_3	Service support required in addition to teachers	19.47
k_4	Books and equipment (lumped with other services in k_3)	NA
k_5	Support for pre-school students entering school in the fall	12.49
k_6	Support for students returning to school in the fall	101.20
k_7	Support for teachers (purchased with their salaries)	10.36
k_8	Total emergy required to support elementary education	167.38
k_9	The energy used in building construction	0.15
k_{10}	The materials used in building construction	14.94
k_{11}	Goods purchased for building construction	0.10
k_{12}	Services used in building construction	0.88
k_{13}	Total emergy of new construction	16.07
k_{14}	Emergy of dropouts with an average fifth grade education	4.33
k_{15}	Emergy of students completing the eighth grade	220.03
Secondary Education (Figure 1b)		
k_0	Renewable resources used on the school grounds	0.21
k_1	Consumption of fuel and electricity to run the schools	0.87
k_2	Depreciation of school buildings (0.0333 per year)	14.76
k_3	Service support required in addition to teachers	9.20
k_4	Books and equipment (lumped with other services in k_3)	NA
k_5	Support for eighth grade graduates entering high school in the fall	13.40
k_6	Support for high school students returning to school in the fall	40.29
k_7	Support for teachers (purchased with their salaries)	7.74
k_8	Total emergy required to support high school education	86.47
k_9	The energy used in building construction	0.10
k_{10}	The materials used in building construction	9.96
k_{11}	Goods purchased for building construction	0.11
k_{12}	Services used in building construction	0.59
k_{13}	Total emergy of new construction	10.72
k_{14}	Emergy of dropouts with an average 10th Grade education	60.08
k_{15}	Emergy of students completing high school	254.18
College/University (Figure 1c)		
k_0	Renewable resources used on the school grounds	0.18
k_1	Consumption of fuel and electricity to run the schools	1.27
k_2	Depreciation of school buildings (0.0333 per year)	21.50
k_3	Service support required in addition to teachers	19.55

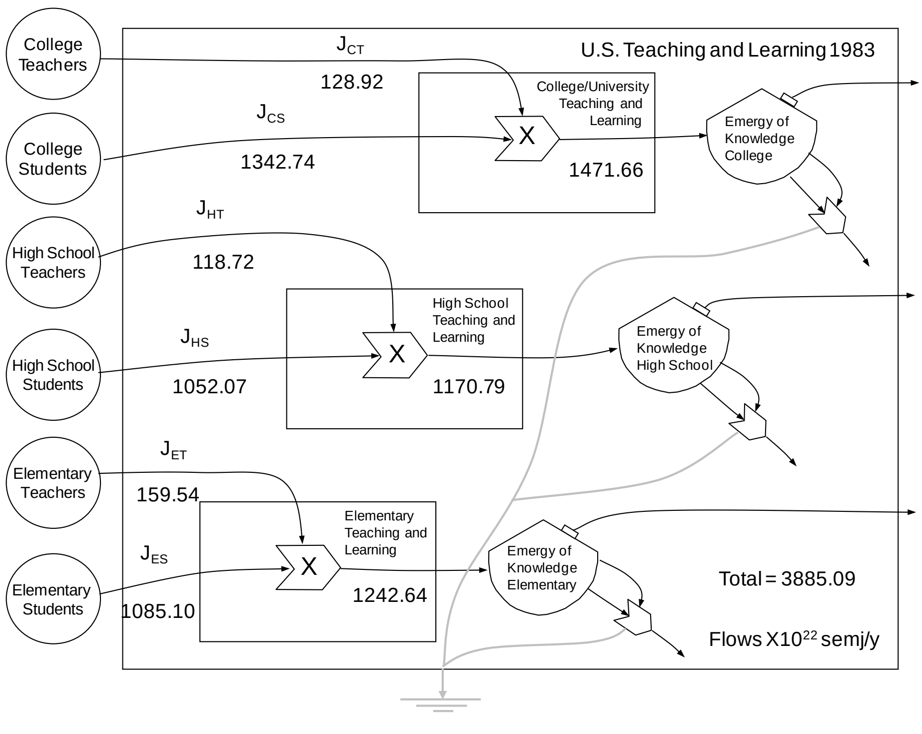
Table 1. *Cont.*

Pathway	Definition of Emergy Flow	Value ×10^{22} (semj/y)
College/University (Figure 1c)		
k_4	Library books	0.85
k_5	Support for high school graduates entering college in the fall	6.50
k_6	Support for college students returning to school in the fall	42.45
k_7	Support for teachers (purchased with their salaries)	7.43
k_8	Total emergy required to support college education	99.73
k_9	The energy used in building construction	0.15
k_{10}	The materials used in building construction	14.52
k_{11}	Goods purchased for building construction	0.10
k_{12}	Services used in building construction	0.86
k_{13}	Total emergy of new construction	15.62
k_{14}	Emergy of associate degrees and college dropouts	47.01
k_{15}	Emergy of college graduates	116.09
k_{16}	Emergy of masters graduates	39.13
k_{17}	Emergy of professional graduates	10.40
k_{18}	Emergy of doctoral graduates	4.89

3.2. Model of Teaching and Learning

Following the ideas of Odum (1996) [1] the higher order social process of teaching and learning (Figure 2) is modeled as a system interaction, in which a few high quality transmitters (the teachers) transfer information to many lower quality receivers (the students).

Figure 2. An emergy evaluation of the process of teaching and learning that occurred within the elementary, secondary, and college/university education subsystems of the United States in 1983.



The emergy of teaching and learning was quantified as the sum of the emergy delivered during the time spent transmitting information plus the emergy brought to the learning process by the receivers, *i.e.*, the students. We assumed that the emergy of the teaching and learning process was all that was required to increase the total knowledge in the system. The energy requirements for maintaining organized information increase in proportion to the number of possible combinations of connections in the system, which is proportional to the square of the number of units organized [26]. Thus, since knowledge is a form of information, the energy requirements for maintaining useful or organized knowledge must increase quadratically to balance losses as shown by the quadratic drains on the knowledge storages in Figure 2. The algorithms for calculating the emergy required for the teaching and learning process are given in Appendix A under *Emergy of Teaching and Learning*.

4. Methods

The standard methods of Emergy Analysis [1,15,27,28] were used to evaluate the education system of the United States. The methods used were those appropriate for evaluating a production process [1]. These methods were applied independently to each of three subsystems, elementary, secondary, and college/university, that together comprise the U.S. education system. The first step in performing an emergy evaluation of a production process is to diagram the process (Figures 1a–c and 2) using the symbols of the ESL [26]. In the process of creating the diagram appropriate spatial and temporal boundaries are determined. The spatial boundaries of this study were set to be the territorial boundaries of the United States including the 48 contiguous states, Alaska and Hawaii. The temporal boundaries of the study were set by the time period evaluated, *i.e*., 1870 to 2011. The time period for each discrete evaluation of the subsystems was one year. The model components, outputs and the required inputs to the education subsystems were determined from our general knowledge of the structure and function of education systems and from a prior study of the University of Florida reported in [1] (p. 233).

In this case, the second step in the evaluation was to decide on the method that we would use to estimate the emergy of the graduates from the three subsystems. We decided that, for this analysis, the fundamental aspect of students was their capacity to store information through learning, so the emergy required to transfer information to the students in a given year could be captured by the sum of the annual emergy inputs required to run the school subsystem. In this method, the emergy of an individual student's education was calculated as the sum of the emergy required for an individual to complete each year of education summed over the time spent in school through graduation or dropout.

The third step was to systematically evaluate each of the inputs required to produce individuals with the various levels of education. Most of the raw data used to evaluate the subsystems were found online in the Statistical Abstracts of the United States: 2012 and Earlier Editions [29], as well as in the Statistical Abstracts of the United States 2012–2013, 131st edition [30] and ProQuest Statistical Abstracts of the United States 2014 [31]. All volumes issued from 1870 to 2014 were used in this evaluation. In addition, we used data on the U.S. education system compiled by [32]. Furthermore, various sources were used to fill-in critical information that was not recorded in the Statistical Abstracts of the United States, e.g., Olsen [33] provided data on the material and labor requirements for building construction. The second task in evaluating the inputs was to determine the algorithm to be used to calculate each input (see Appendix A). The amount of each input was determined first in the units in which it is commonly expressed, e.g., individuals for people, grams for mass, joules for energy, and $ for economic flows.

The fourth step in evaluating the education process of the U.S. was to convert the values for the inputs from their common units into emergy by multiplying by the appropriate Unit Emergy Value (UEV), *i.e.*, the emergy per person (semj/ind) for people, the transformity (semj/J) for energy, the specific emergy (semj/g) for mass, or the emergy to money ratio (semj/$) for money flows. The emergy inputs to each subsystem were then summed to determine the emergy required to support the educational process at that level in any given year. The emergy per individual for graduates or dropouts from any subsystem was determined by summing the annual emergy use required for their support during their time in school. The emergy required for all earlier education, including pre-school, was included in the emergy of an individual who had attained higher levels of education. The transformity (semj/J) of the work done by an individual with a given number of years education was calculated by dividing the emergy per individual by the metabolic energy expended by an individual in a year. The implicit assumption for this calculation to be valid is that a person will draw upon the majority of the information that they possess in the performance of the work done over the course of a year and that all of the daily activities of the person are necessary to support their ability to apply their knowledge and experience during their working hours. Other choices for these parameters are also plausible, but were not investigated in this study.

"Teaching and learning" was evaluated as a higher order social process requiring the emergy of both interacting inputs (see Appendix A). The emergy delivered in the teachings conducted in a subsystem is the emergy of the teacher's education and experience per individual times the fraction of hours spent on teaching times the number of teachers. The student's emergy, which is required to receive the information, is the emergy of their average education level per individual times the fraction of hours spent learning times enrollment. The sum of these two inputs is the emergy of "teaching and learning" that occurs within each subsystem. The sum of the three subsystems is the emergy of teaching and learning occurring within the formal education system of the United States in any given year.

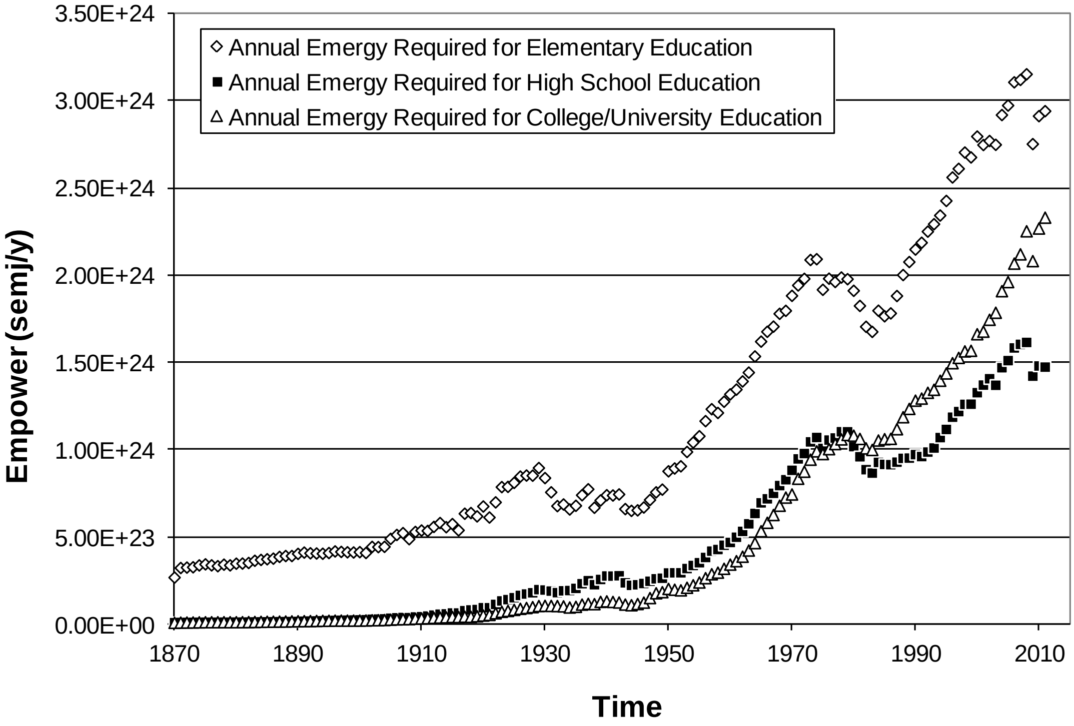
5. Results

The primary results of this study are reported in Appendix B as a table of values showing the emergy required to educate individuals to achieve varying levels of education from preschool to the doctoral degree with 2 years postdoctoral experience. The values of the emergy per individual are based on the emergy inputs to the U.S. given in [34,35]. Other results of this study are reported in the text, figures and tables presented below.

The large scale pattern of growth in the empower (*i.e.*, emergy flow in semj/y) of all three levels of education in the U.S. (Figure 3) has been driven by population growth as shown by the growth in enrollment (Figure 4) and by the expansion of the fuel and mineral resources supporting the U.S. economy [34,35]. Within this large scale pattern we can observe some interesting features. In 1983, the empower of elementary education was 1.94 times that of high school and 1.68 times that of the college/university education subsystem (Figures 1 and 3). This relationship has varied over time, but elementary education's empower has exceeded that of the other two subsystems over the entire period. College education's empower first exceeded high school education in 1980, when it was 5.7% greater.

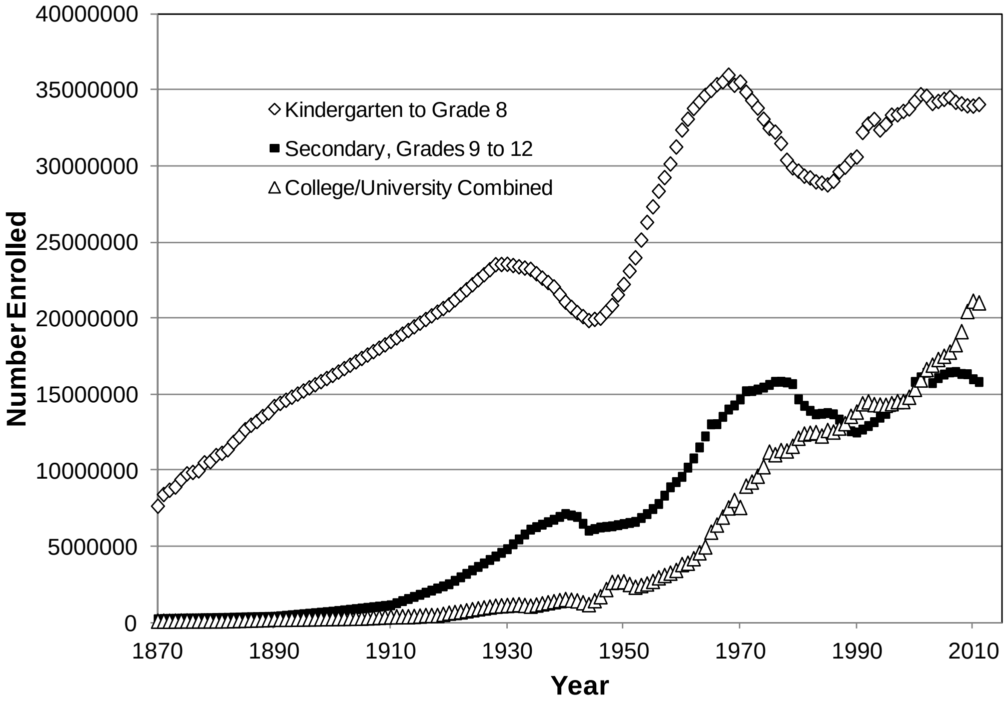
After 1983, the emergy supporting both college and elementary education began to increase rapidly, but the time of rapid increase was delayed until 1993 for high school as the increase in elementary enrollment moved through the system (Figure 4). The structure of the inputs to all three subsystems followed a similar general pattern with some differences. The emergy of returning students was always the largest input to all subsystems, but the second largest input varied among the subsystems, e.g., in 1983 (Figure 1) the second largest input to the elementary and college subsystems was purchased services, whereas entering eighth grade graduates supplied the second largest emergy input to secondary schools. Purchased services, as a percent of total emergy use, are relatively more important in the college/university subsystem than in the elementary and secondary subsystems.

Figure 3. The annual emergy required to support the elementary, secondary, and college/university subsystems (the k_8 pathways in Figure 1) of the education system of the United States from 1870 to 2011.



In general, the emergy of the inputs to all three education subsystems followed an increasing trend from 1870 to 2011 with periods of decline and fluctuation corresponding to sometimes different and sometimes similar sensitivities to the major socioeconomic events of the past 142 years (Figure 3). Note the marked decline in emergy supporting elementary education during the Great Depression (GD) and the GD's smaller effect on the emergy supporting secondary and college education. In contrast, the emergy support for all three subsystems drastically declined in 2009 in response to GR08; however the annual empower of the college subsystem recovered to its 2008 level in 2010 while the emergy flow supporting the elementary and secondary levels remained depressed through 2011. An observation that helps explain this pattern in emergy use by the subsystems is that enrollment in college markedly increased in 2008 (Figure 4), while elementary and secondary enrollment continued to follow the existing trends established by the population of elementary and secondary students.

Figure 4. Annual enrollment in the elementary, secondary, and college/university subsystems of the education system of the United States from 1870 to 2011.



The amount of information transferred as measured by the emergy of the process of teaching and learning in the 1983 school year is shown in Figure 2. The annual emergy required to support teaching and learning in the elementary school subsystem exceeded the secondary school subsystem by 6.1%; whereas, the emergy supporting teaching and learning at the college/university level exceeded secondary school subsystem by 25.7% and the elementary subsystem by 18.4%. In 1983, the emergy of the process of teaching and learning exceeded the annual emergy required for school operations by 7.4 times for elementary, 13.5 times for secondary, and 14.8 times for college/university education (Figures 2 and 5). The unweighted average with the standard deviation of these ratios is 11.9 ± 3.95, which is approximately an order of magnitude difference.

Figure 5 shows the time history of variation in the emergy of teaching and learning in the three U.S. education subsystems (Figure 2). Until 1977, the emergy of teaching and learning is greatest at the elementary level. After 1977, high school briefly accounted for the largest emergy flow until 1980 when the emergy of teaching and learning at the college level became the largest. Since 1980, teaching and learning in the college/university subsystem has continued to increase, maintaining its position as the largest educational activity in the U.S. as measured by the emergy of the information transferred. The emergy of teaching and learning in the elementary subsystem declined slowly from 1976 to 1986 after which it began to increase. The high school subsystem declined from 1979 to 1989 and then after 1991 it began to increase at a rate similar to the increase of the emergy of teaching and learning in college/university and elementary subsystems. After 1995 the rate of increase in the emergy of teaching and learning in the college/university subsystem became more rapid, separating it from the rates of increase of both the elementary and secondary education subsystems. This rapid growth continued until 2011, the last year of data available to us, when it suddenly stopped, *i.e.*, the emergy of teaching and learning at the college level in 2011 was almost the same as in 2010.

Figure 5. The annual emergy flow (empower) of teaching and learning in the elementary, secondary and college/university education subsystems of the United States from 1870 to 2011.

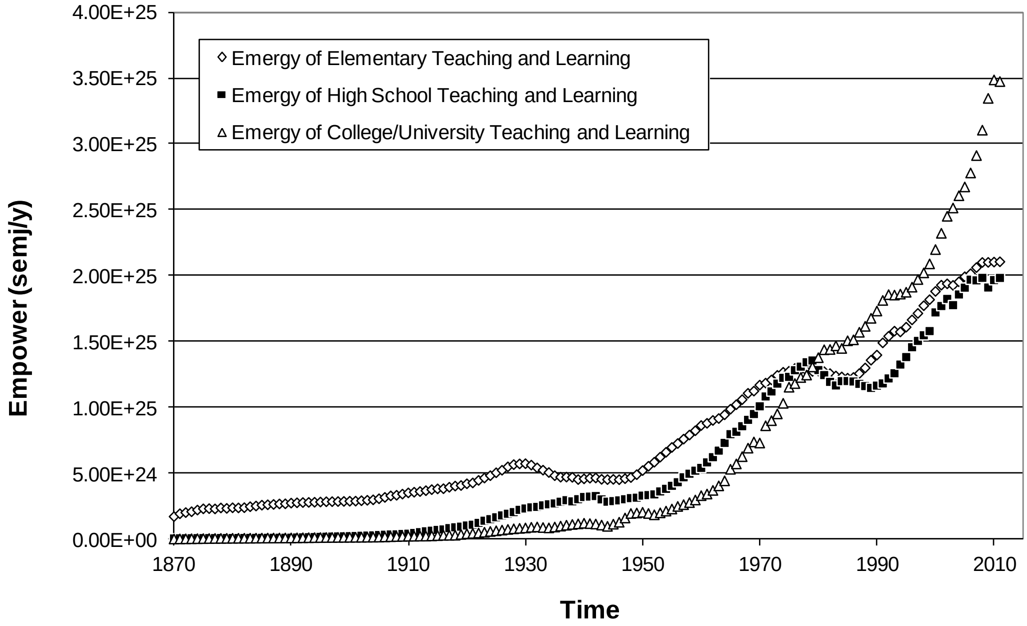
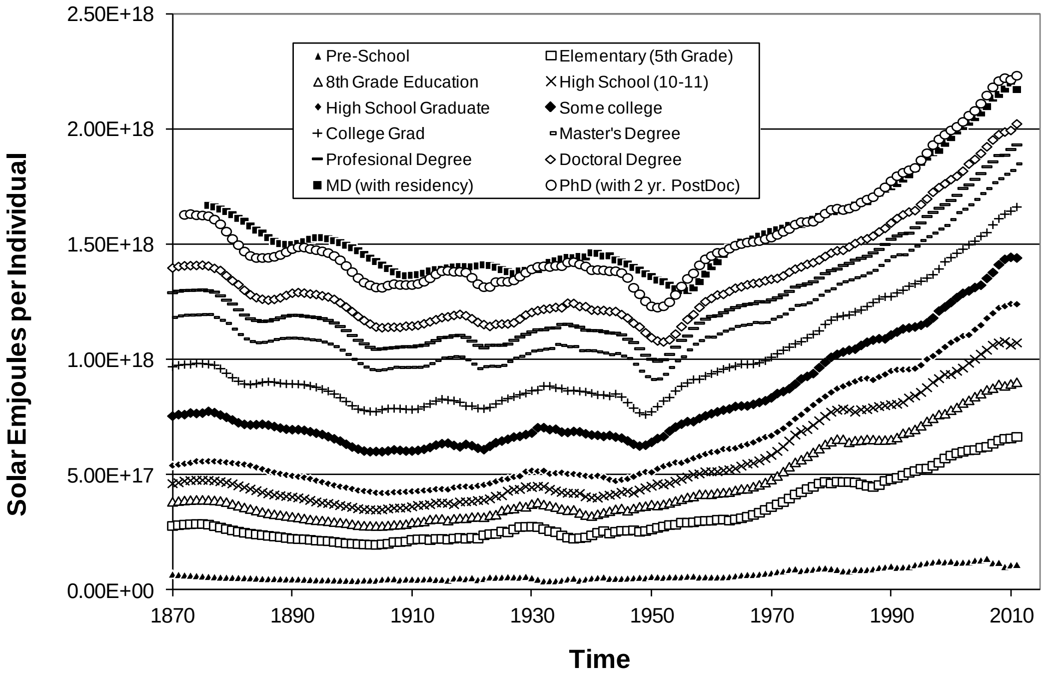


Figure 6. The emergy per individual required to create knowledge (*i.e.*, by storing information with the instructions on how to use it) at twelve levels of education (*i.e.*, primary, secondary, college/university and their subsets) within the United States from 1870 to 2011 (see Appendix B).



Time series of the emergy per individual for twelve education levels from pre-school to the doctoral degree plus 2 years postdoctoral experience are shown in Figure 6 (see Figure 1 for 1983 values). The numerical values for the emergy per individual at these education levels are given in Appendix B in tabular form for use in future emergy analyses. The emergy per individual in this table is the summation of the emergy required annually at each level to support the student up to the point he or she leaves school. The emergy of education per individual in all categories declined from 1870 to varying inflection points, which occurred in most cases during the first 5 years of the new century. After this time, the emergy of education per individual began to increase and it continued to do so in most categories until varying times during the Great Depression. From this high point, the emergy per individual declined with some variation depending on education level to an inflection point occurring around 1950. After this time the emergy of education per individual for high school graduates and higher has increased almost monotonically to the present time. A general pattern is noticeable in the data, in which the inflection point in the emergy required per graduate is lagged in time for higher levels of education, *i.e.*, longer times in school. For example, after WWII, the turnaround in emergy support for education was later for progressively higher education levels (*i.e.*, 1945 for high school graduates, 1952 for graduate degrees and 1957 for MDs).

Table 2. Emergy per individual and the transformity or the emergy delivered per joule of metabolic work for different education levels in the United States in 1983.

Attainment	Odum 1996 [1] ^ Emergy/ind. (E+16 semj/ind./y)	Transformity * (E+6 semj/J)	This study # Emergy/ind. (E+16 semj/ind./y)	Transformity * (E+06 semj/J)
Preschool	3.4/5.7	8.9/14.9	8.63	22.6
School	9.4/15.8	24.6/41.2	47.3	123.8
College Graduate	28.0/46.9	73.3/122.8	119.7	313.3
Masters			135.0	353.4
(Post College Ed.)	131.0/219.5	343.0/574.6		
Professional			142.2	372.3
Ph.D.			149.2	390.6
Public Status	393.0/658.4	1029.0/1723.9	552.5	1446.3
Legacies	785.0/1315.1	2054.0/3441.1		

^ The emergy and transformity values for the levels of educational attainment from [1] are reported first using the emergy base for the U.S. (7.70E + 24 semj/y) as determined by Odum [1] and second using the emergy base for the U.S. for 1983 (1.29E + 25 semj/y) as determined in this study. Also, these values are generally consistent with the calculations for levels 3–5 in Abel [24]. # In this table, school assumes education through grade 5, college assumes 2 years study, professional assumes a 3 year degree and public status assumes that 1% of the population meets this criterion. ***** Energy per individual (ind.) [1] (p. 232): (2500kcal/day) × (365days/yr) × (4186J/kcal) =3.82E+09 J/ind/yr.

We compared the emergy per individual and the transformity of the work done by individuals with various levels of education as calculated in this study to earlier results from Odum [1] (Table 2). A solidus or slash separates Odum's results as he originally calculated them from the values obtained after adjusting his calculation using the emergy base for the United States in 1983 given in [34,35]. The emergy inflows to the U.S. reported in an earlier version [35] of [34] are slightly different from those used in this study. Estimates from this study exceed the adjusted estimates from Odum [1] for preschool, school, and college education by 1.56, 3.07, and 2.27 times, respectively. However, Odum's adjusted estimate for post-college education exceeds our average post-college estimate by 1.52 times. If one percent of the population has attained public status as we assumed, Odum's estimate for the emergy of an individual with public status is 17% greater than the estimate made in this study. "Public Status" implies that an individual controls energy, material, and information flows that are larger than expected for a person with their education level, e.g., for a public official managing a National Park, or a CEO of a large company, experience may be the largest factor in determining the transformity of their work.

6. Discussion

In most published databases, flows of energy, materials and labor are quantified in monetary units; whereas, emergy analysis primarily needs information quantified in physical units of mass, energy or information. Consequently, estimating the emergy equivalent of a monetary flow is sometimes the only possible way to quantify all the inputs to a production process or a territorial system, e.g., a nation, state, or county. In an emergy evaluation, the Emergy to Money Ratio (EMR) is the metric commonly used to convert a money flow expressed in dollars to an estimate of the associated emergy flow; however, this conversion is only a rough approximation of the emergy of the human work required to produce the item. With this concern in mind, we wanted to make an independent estimate of the emergy for which a quantity of money is paid, assuming that money is paid only for the knowledge and experience delivered by the intellectual and physical labor required to produce a product or service.

In this study the education level of the worker is largely responsible for our estimates of the quality-adjusted work performed by individuals (Appendix B); however, we recognize the importance of experience and we included it in this study, when possible, as explained in the next section. In any case, the emergy of an individual's experience could be documented in the same manner as we determined the emergy of an individual's education, *i.e.*, by calculating the emergy required to support the time spent in learning while on the job (Appendix A: *Emergy of Teaching and Learning*).

6.1. Comparison of Estimation Methods

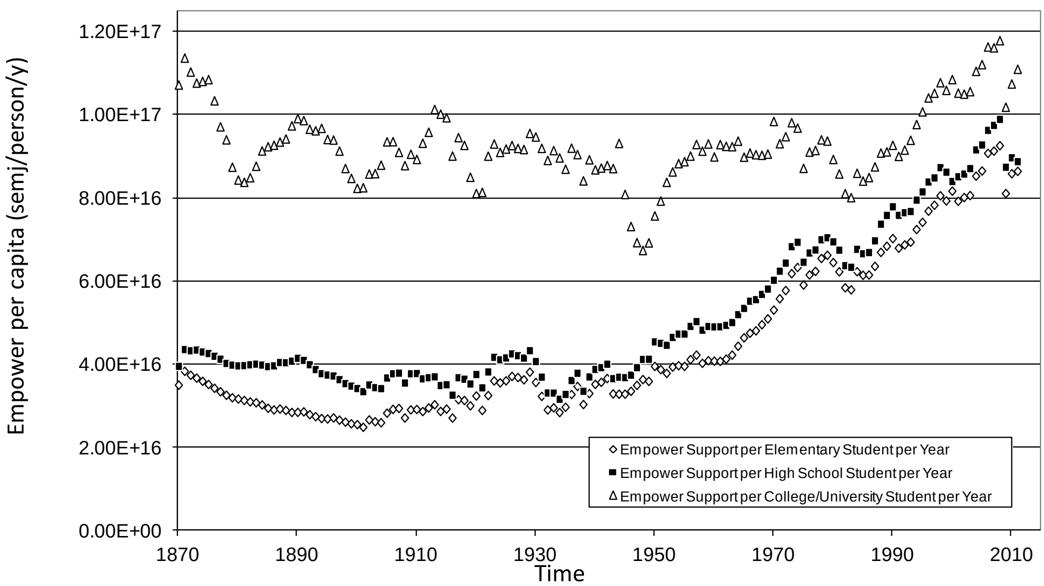
Our estimate of the transformity of knowledge was based on quantifying the emergy required for the education of an individual, which we assumed captured most of the emergy delivered in the work done, for which money was paid. As described above, the knowledge of individuals was quantified through performing an emergy analysis of the U.S. education system from 1870 to 2011. In the future, the value of experience also should be quantified to obtain the best estimate of the emergy delivered in a joule of a person's metabolic work. However, we quantified both the average number of years of education and experience of the teachers in each subsystem as a model input and as part of the internal calculations within the model (see Appendix A). We quantified the experience of students as they passed through the education subsystems to graduation; however, in this case we considered their education and experience to be the same thing. The emergy of the experience of doctors performing internships and residencies was quantified as was the experience of a Ph.D. in postdoctoral study. In both cases, we assumed that the emergy required to gain experience was similar to that required to educate university students. Similar methods might be used to quantify the emergy of experience for other occupations as this method matures. In this study, we proposed that a quasi-independent estimate of the emergy flow for which money is paid, *i.e.*, the emergy of the knowledge and experience delivered in the work of individuals, would allow us to calculate the emergy of educational attainment in the United States over time and to include this input as part of the emergy basis for characterizing and analyzing socioeconomic activities of the nation and of people [36,37].

Odum [1] estimated the emergy delivered by the work done at various education levels by assuming that the total emergy inflow to the nation in a year supported the observed distribution of educational attainment. The number of people that had achieved each level of attainment was divided into the emergy base for the nation in that year to estimate the emergy per individual with a given number of years of education. The output was a series of transformities that increased with education level, because almost everyone had achieved a preschool level of education, but only 6 million people had post college education. This method assumes that the system is in steady state and that all of the emergy input to the nation is what was required to produce the hierarchy of observed education levels in the year evaluated. In this paper, we estimated the emergy of human service based on an emergy evaluation of the education system in the United States under the assumption that the emergy supporting an individual in this system, when summed over the time spent in school, captured the emergy required to produce an individual with a given number of years of education. In this method, we do not need to assume that the system is in steady state, because we have the data to document the change in the state variables of interest in each year, nor must we assume that the entire emergy of the nation is required to produce the individuals at each education level. Even though the variables of interest are in flux from year to year, we have used the assumption of steady state when estimation or extrapolation was used to obtain missing values. Our method, which is based on determining the cumulative emergy required for a given level of education, resulted in a higher assessment of the emergy per individual for college, high school, elementary and preschool, but a lower estimate for post-graduate education than found in [1]. This result is, in part, due to the use of the total number of people who had attained an education level as the basis for Odum's calculation compared to our use of summation over the years in school up to the final level of education attained. Odum's method is more holistic and top-down in that it relies only on the emergy use of the nation and educational attainment to estimate the emergy per individual, but it has some significant difficulties related to the reasonableness of its underlying assumptions, *i.e.*, it assumes that the education system of the U.S. is in steady state and that the details of the system are not important and perhaps unchanging, if his numbers for 1983 are applied to other years and places. The method used in this paper makes the plausible argument that all students learn from their time in school and that all other things being equal the emergy required for a step in learning is proportional to the emergy required to support the students and the school system during their time in school. Of course, all other things are not equal because students vary in intelligence, dedication to their studies, learning styles as well as in other ways. These secondary factors were not considered in this analysis. Given the fact that the two methods use different approaches, it is encouraging that the results from both methods are in the same "ballpark" and that the variation is consistent with the differences expected from the inherent characteristics of the calculation methods used. For example, since our calculations are more detailed and ostensibly more complete, one would expect our numbers to be higher than Odum's and this is true for education levels below post-graduate. However, Odum's numbers for the emergy of an individual with a post-college education are somewhat higher than ours, possibly because of the smaller number of people in this class and because he used the entire emergy of the nation to determine the emergy per individual rather than the emergy actually used to support their education.

6.2. Temporal Patterns in the Emergy Measures of the Education Subsystems

We observed patterns in the time series of variables used to characterize the three education subsystems. For example, we noticed a broad pattern of increase in all inputs to all subsystems over the entire period of the analysis except for the input from the environment to the elementary education subsystem and to a lesser extent from the environment to the secondary education subsystem. Input from the environment to the elementary school system peaked from 1927 to 1929 after which it rapidly declined, apparently due to the consolidation of small schools into larger ones, thus requiring less total land area. Also, we observed a pulse with a long period of increase and rapid decline, which is seen in the temporal pattern of the emergy required to support the elementary and secondary school systems from 1950 to the late seventies, which can be explained, in part, by the population cycle driven by the post WWII "baby boom". The consistent decline in the emergy of education per individual with a given level of education at all education levels from 1870 to 1900 is due to factors not related to the efficacy of the work performed by a person of a given educational status. This pattern is seen because the number of students enrolled in school at all levels increased rapidly during this period, while the emergy of the inputs to the educational system increased less rapidly.

Figure 7. The emergy per student per year used by each subsystem of the education system of the United States from 1870 to 2011.



A different perspective on education in the United States can be gained from examining the emergy invested per student per year in each subsystem (Figure 7). The pattern of annual emergy use to support a college/university student remained relatively constant from 1901 until 1983 varying between 8.0E+16 and 1.0E+17 semj/ind./yr with the exception of the period from 1945 to 1951, when soldiers were returning to school on the GI bill. After the transition decade from 1974 to 1983 during which petroleum was replaced as the largest energy source for the United States by electricity from nuclear power and coal [34,35] and the rapid growth in the use of personal computers starting in the early 1980s, which ushered in the Information Age; the annual expenditure of emergy per college student began an almost linear increase that continued until 2008. Two fluctuations occurred along this path: a minor decline associated with the recession of 1991 and a larger decline (2001–2003) associated with the bursting of the internet or "dot-com" bubble of inflated values in the stock market and in society as a whole. This linear advance ended with a precipitous decline in the emergy invested per student for all education subsystems beginning in 2009 and from which the subsystems had not recovered by 2011.

The emergy support per student in the elementary and secondary subsystems shows a closely related pattern over the time examined that is different from the pattern exhibited by college/university education. The emergy invested per student declines from 1870 to 1900 for the reasons given above, but from 1901 until 1929 the emergy invested per student generally increased with some fluctuations. From the middle of the GD (1929 to 1934), emergy expenditures on primary and secondary education decline. After 1934 the emergy invested per student rises, first with a linear trend, which was interrupted by the 1957–1958 recession and then with an apparently exponential trend, which continues until 1974, the beginning of the transition period mentioned above. From 1974 to 2011, elementary and secondary education follow a pattern similar to that described for college/university education. The most striking characteristic of the pattern of annual emergy use per student in elementary and secondary education is that it remained in a relatively constant relationship with college education from 1900 to 1934, with expenditures varying from 30% of college expenditures in 1901 for elementary education to 45% in 1929 for secondary education. However, from 1934 to 2008 the amount of emergy invested per student rose in both the elementary and secondary subsystems until, in 2008, society's emergy investment in elementary and secondary education per student was 79% and 84%, respectively, of that invested in college education. The rapid growth of the emergy invested per student from 1983 to 2008 may reflect the resource expenditures necessary to support the transition of the nation into the Information Age. This transition was characterized first by learning to incorporate computer use into daily activities (1981 to 1995) and second by learning how to use access to the knowledge available on the internet (1995 to the present) to increase the effectiveness of our work in an increasingly complex world, and thereby strengthen the fabric of society.

6.3. Technical Obstacles

One of the primary obstacles that had to be overcome in carrying out this research was that we wanted to estimate the emergy of an individual with a given number of years of education in a manner that was as independent as possible from estimates based on monetary measures of the inputs. Therefore, we needed to make the calculations without using the emergy to money ratio of the nation to determine the emergy supporting the education levels. We imposed this condition on our analysis, because we intend to use the emergy required for the education of an individual as a measure of the emergy that this individual contributes to society through the knowledge delivered in the work that they do and for which they are paid. If the estimate of the emergy of education is relatively free of monetary influences, we can use the emergy required to produce the information delivered in the paid work done by people at a certain education and skill level as an independent estimate of the emergy delivered to the economy in that work, which in turn will allow us to establish a relatively unbiased complete emergy base for a national economy, *i.e.*, an emergy base that includes the emergy of the material and energy inputs from the environment and the emergy of information delivered in both the intellectual and physical work of people in a manner that is not confounded [16].

6.3.1. Why the Method is Quasi-Independent of Monetary Measures

The complete avoidance of monetary measures proved to be a task beyond our capabilities; therefore, we settled for a quasi-independent estimate using the EMR only when absolutely necessary. The EMR of the U.S. was used to estimate two important inputs to the analysis. First, we used it to estimate the emergy required to support students and teachers. In the former case, we used the share of the emergy of the nation as represented by the disposable income per individual to estimate the emergy that could be used to support an average student. In the latter case, the emergy used to support teachers was calculated using their salary and the EMR in the year being evaluated. In the former calculation, an error is introduced by assuming that a student of any age will get an equivalent share of disposable income within a family. Also, we might have made a more accurate estimate of the emergy used to support students by using the median instead of the average disposable income in the estimation. Thus, our estimate of the emergy required for student support may be somewhat too high and biased by overestimating the annual support needed for an elementary school student and underestimating that needed for a college student. In the latter calculation, the emergy that can be purchased by a teacher's salary is probably a fairly accurate estimate of the resources available for their support.

Second, the service required for school operations and construction was estimated using the current EMR in the year evaluated. In this case, we estimated the material and energy flows separately and the dollars paid for services should reflect the emergy required for the purchased work of people, if the services are being delivered by labor with the average transformity of the system. Most other inputs were estimated from the emergy of energy, material and information flows; and therefore, we believe that we have made a reasonable first-order, quasi-independent estimate of the emergy per individual at the various education levels in the United States from about 1900 to 2011. We do not recommend that the years from 1870 to 1899 be used as accurate estimates of the emergy per individual at the various education levels, since we allotted this time for the calculation to stabilize (see below).

6.3.2. Method Used to Deal with Unknown Initial Conditions

A second difficulty, in performing these calculations, was that we needed to know the initial condition of several variables, e.g., the emergy of school buildings, the emergy of teacher's education, *etc*., in order to make an accurate estimate of the annual emergy flows required for education in the first year of the analysis. We dealt with this problem by starting our analysis in 1870 rather than in 1900, when the storages, e.g., school buildings, enrollment, number of teachers, *etc*., were very small compared to later years. By starting the analysis in 1870 when storages and flows were small, errors in the initial estimates were not so important, and we could allow the evaluation to "spin up" as each year of new data was added, in a manner similar to the simulation of a mathematical model with uncertain initial values. In about 10 years the output variables had stabilized and were following reasonable trends. Our initial estimates might be improved in the future by applying an iterative approach to the calculation of the emergy of the education levels by constructing a model and feeding back the current estimates as initial conditions and annual inputs iteratively until a stable value for the emergy per individual at each education level is reached.

6.3.3. Lack of Consistency in Some Measurements

There is a lack of consistency in some of the numbers currently used in our evaluation for some years. These variations occur because the U.S. Census Bureau reports many different versions of a number like elementary enrollment. In addition, one accounting method will be used for a series of years and then changed, leading to different methods for making the estimate. Furthermore, the values that are first reported often are refined in subsequent years, so it was difficult to eliminate all inconsistencies from the reported values of some variables. Wherever possible we have tried to remove inconsistency by checking numbers against more than one source in the database; however, inconsistency in reporting still leads to some noise in the data, but it is small compared to the first and even second order trends, *i.e.*, we do not believe that the discrepancies in the data are large enough to affect the results of the study. In general, variations of our estimates are within the ±10% bounds acceptable for emergy analyses [15,28]. Also, many variables that were used in this analysis had missing data for one or more years. We handled missing data using three techniques, interpolation, extrapolation, and estimation. Interpolation and extrapolation were used when we had values for many years over the 142 year period. Estimation was used when we had little information and needed to impute reasonable values for a variable. Linear interpolation between two known values and proportionate extrapolation using the relationship between a known variable and the unknown to assign values to the unknown were used to assign values to the years with missing data.

6.4. The Emergy of Teaching and Learning

Odum [1] described the method for calculating the emergy of teaching and learning, and we followed his method in our spreadsheet calculations. Our calculation of the emergy of teaching and learning is one of the first calculations of the emergy of a higher order social process, but see [38]. We refer to “teaching and learning” as a higher order social process because it depends on a complex underlying series of energy transformations supporting education, and it evaluates with transformities that are approximately an order of magnitude greater than the underlying annual support for operating the education system (e.g., for elementary education in 1983 (Figures 1 and 2) we have, 1320.72 semj/171.41 semj = 7.7, for the ratio of the annual emergy of elementary teaching and learning to the annual support emergy for elementary education. The emergy of teaching and learning is a measure of the emergy required for copying or transferring information [1,14] vital to the functioning and continuance of society, and as such it is a higher order social function, which has a transformity approximately an order of magnitude greater than that required for the annual support of the U.S. education. The implication of this result is that the emergy spent annually on education has about a 10:1 return on investment in terms of the overall benefits gained by society through the transfer of information vital for its continuance. The importance of teaching and learning to maximizing empower of the nation is particularly apparent in the exponential increase of teaching and learning empower at the college/university level during the Information Age (1981 to present).

7. Conclusions

We developed a model-based empirical evaluation method for tracking the emergy required for an individual to achieve various levels of education in the United States from 1870 to 2011. We provided a data table giving the emergy required to produce individuals at 12 different levels of education for each year from 1870 to 2011 for use in subsequent emergy evaluations. We demonstrated that our method gave results that were plausible when compared to the earlier results of Odum [1], which were determined using a different method. We evaluated "teaching and learning" in elementary, secondary and college/university subsystems of the U.S. education system and we characterized it as a higher order social process with an emergy amplification effect 10 times the emergy invested in operating the school systems. Temporal patterns of the emergy invested per student per year were indicative of educational priorities; practical realities, such as wars and population cycles; as well as the necessity of providing better education to help society incorporate the advances of industrial and information technology over the past 142 years. By quantifying the emergy of the information delivered to a national system by the work of individuals with various levels of education, we have taken a first step toward making a quasi-independent estimate of the emergy supplied to that nation through the knowledge delivered from the educational attainment of its workers in their work performed annually within the system boundaries.

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Author Contributions

Dan Campbell was the primary author of this paper and principal researcher accounting for 90% of the writing and 75% of the research and analysis. Hongfang Lu gathered data and performed some of the analyses. She carried out and checked the spreadsheet calculations, read and criticized the draft paper, and provided intellectual input in developing the theory and methods used in the paper. Her contribution was 10% of the writing and 25% of the emergy evaluation and methodology.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Odum, H.T. *Environmental Accounting: Emergy and Environmental Decision Making*; John Wiley and Sons: New York, NY, USA, 1996.
2. Lotka, A.J. Contribution to the energetics of evolution. *Proc. Nat. Acad. Sci. USA* **1922**, *8*, 147–151.
3. Lotka, A.J. Natural selection as a physical principle. *Proc. Nat. Acad. Sci. USA* **1922**, *8*, 151–154.

4. Lotka, A.J. *Physical Biology*; Williams and Wilkins: Baltimore, MD, USA, 1925.
5. Vernadsky, V.I. The biosphere and the noösphere. *Am. Sci.* **1945**, *33*, 1–12.
6. Vitousek, P.M.; Mooney, H.A.; Lubchenco, J.; Melillo, J.M. Human domination of Earth's ecosystems. *Science* **1997**, *277*, 494–499.
7. Campbell, D.E.; Lu, H.F.; Knox, G.A.; Odum, H.T. Maximizing empower on a human-dominated planet: The role of exotic *Spartina*. *Ecol. Eng.* **2009**, *35*, 463–486.
8. Vitousek, P.M.; Aber, J.D.; Howarth, R.W.; Likens, G.E.; Matson, P.A.; Schindler, D.W.; Schlesinger, W.H.; Tilman, D.G. Human alteration of the global nitrogen cycle: Sources and consequences. *Ecol. Appl.* **1997**, *7*, 737–750.
9. Campbell, D.E.; Lu, H.F.; Lin, B.L. Emergy evaluations of the global biogeochemical cycles of six biologically active elements and two compounds. *Ecol. Model.* **2014**, *271*, 32–51.
10. Brown, M.T.; McClanahan, T.R. Emergy analysis perspectives of Thailand and Mekong River dam proposals. *Ecol. Model*. **1996**, *91*, 105–130.
11. Brown, M.T.; Ulgiati, S. Emergy measures of carrying capacity to evaluate economic investments. *Popul. Environ.* **2001**, *22*, 471–501.
12. Lu, H.F.; Campbell, D.E. Ecological and economic dynamics of the Shunde agricultural system under China's small city development strategy. *J. Environ. Manag.* **2009**, *90*, 2589–2600.
13. Lu, H.F.; Lin, B.L.; Campbell, D.E.; Sagisaka, M.; Ren, H. Biofuel *vs*. Biodiversity? Integrated emergy and economic cost-benefit evaluation of rice-ethanol production in Japan. *Energy* **2012**, *46*, 442–450.
14. Odum, H.T. Limits of Information and Biodiversity. In Sozialpolitik und Okologieprobleme der Zukunft, Festsymposium der Osterreichischen Akademie der Wissenschaften analaslich ihres 150jahrigen Jubilaums 14. Bis 16. Mai 1997; Loffler, H., Streissler, E.W., Eds.; Verlag der Osterreichischen Akademie der Wissenschaften: Wien, Austria, 1999; pp. 229–269.
15. Campbell, D.E.; Ohrt, A. *Environmental Accounting Using Emergy: Evaluation of Minnesota*; USEPA Project Report, EPA/600/R-09/002, 2009. Available online: http://www.epa.gov/nheerl/download_files/publications/MNEmergyEvalfinal2009_1_16.pdf (accessed on 2 April 2014).
16. Campbell, D.E. Keeping the books for the environment and society: The unification of emergy and financial accounting methods. *J. Environ. Account. Manag.* **2013**, *1*, 25–41.
17. Odum, H.T. Living with complexity. In *Crafoord Prize in the Biosciences, 1987*; Crafoord Lectures, Royal Swedish Academy of Sciences: Stockholm, Sweden, 1987; pp. 19–85.
18. Odum, H.T. Self-organization, transformity, and information. *Science* **1988**, *242*, 1132–1139.
19. Campbell, D.E.; Lu, H.F. The Emergy Basis for Formal Education in the United States. In *Emergy Synthesis 5, Theory and Applications of the Emergy Methodology*; Brown, M.T., Sweeney, S., Campbell, D.E., Huang, S.L., Ortega, E., Rydberg, T., Tilley, D.R., Ulgiati, S., Eds.; The Center for Environmental Policy, University of Florida: Gainesville, FL, USA, 2009. Presented at the 5th Biennial Emergy Research Conference, Gainesville, FL, USA, January 2008.
20. The 2012 Statistical Abstract: Earlier Editions. Available online: http://www.census.gov/compendia/statab/past_years.html (accessed 2 April 2014).

21. Bergquist, D.A.; Ingwersen, W.; Liebenow, D.K. Emergy in Labor—Approaches for Evaluating Knowledge. In *Emergy Synthesis 6: Theory and Applications of the Emergy Methodology*; Brown, M.T., Sweeney, S., Campbell, D.E., Huang, S.L., Ortega, E., Rydberg, T., Tilley, D.R., Ulgiati, S., Eds.; The Center for Environmental Policy, University of Florida: Gainesville, FL, USA, 2011. Presented at the 6th Biennial Emergy Research Conference, Gainesville, FL, USA, January 2010; pp. 501–507.
22. Martin, J.F.; Roy, E.D.; Diemont, S.A.W.; Ferguson, B.G. Traditional Ecological Knowledge (TEK): Ideas, inspiration, and designs for ecological engineering. *Ecol. Eng.* **2010**, *36*, 839–849.
23. Diemont, S.A.W.; Martin, J.F.; Levy-Tacher, S.I. Emergy evaluation of Lacandon Maya indigenous swidden agroforestry in Chiapas, Mexico. *Agroforestry Syst.* **2006**, *66*, 23–42.
24. Abel, T. Human transformities in a global hierarchy: Emergy and scale in the production of people and culture. *Ecol. Model.* **2010**, *221*, 2112–2117.
25. Abel, T. Culture in cycles: Considering H.T. Odum's 'information cycle'. *Int. J. Gen. Syst.* **2013**, *43*, doi:10.1080/03081079.2013.852188.
26. Odum, H.T. *Ecological and General Systems: An Introduction to Systems Ecology*; University Press of Colorado: Niwot, CO, USA, 1994. Revised edition of *Systems Ecology*; Wiley: Malden, MA, USA, 1983.
27. Brown, M.T.; Ulgiati, S. Emergy analysis and environmental accounting. *Encyclopedia Energ.* **2004**, *2*, 1–25.
28. Campbell, D.E.; Brandt-Williams, S.L.; Meisch, M.E.A. Environmental Accounting Using Emergy: Evaluation of the State of West Virginia. USEPA Research Report, USEPA/600R-05/006, 2005. Available online: http://www.epa.gov/nheerl/download_files/publications/wvevaluationposted.pdf (accessed on 2 April 2014).
29. U.S. Census Bureau. The 2012 Statistical Abstract: Earlier Editions. 2012. Available online: http://www.census.gov/compendia/statab/past_years.html (accessed on 2 April 2014).
30. U.S. Dept. Commerce. *Statistical Abstracts of the United States: 2012–2013*, 131st ed.; Sky Horse Publishing, Inc.: New York, NY, USA, 2012; pp. 143–192.
31. ProQuest. *ProQuest Statistical Abstracts of the United States 2014*; Bernan, Rowman and Littlefield: Lanham, MD, USA, 2014; pp. 155–205.
32. Snyder, T.D. *120 Years of American Education: A Statistical Portrait*; National Center for Education Statistics, U.S. Department of Education: Washington, DC, USA, 1993. Available online: http://nces.ed.gov/pubs93/93442.pdf (accessed on 2 April 2014).
33. Olsen, J.G. Labor and Material Requirements for Federal Building Construction. Monthly Labor Review Productivity Reports. 1981; pp. 47–51. Available online: http://www.bls.gov/opub/mlr/1981/12/rpt2full.pdf (accessed on 2 April 2014).
34. Campbell, D.E.; Lu, H.F.; Walker, H. Energy and emergy as forces driving money flow in the United States from 1900 to 2011. *Frontiers Energ. Syst. Pol.* **2014**, submitted.
35. Campbell, D.E.; Lu, H.F. The Emergy to Money Ratio of the United States from 1900 to 2007. In *Emergy Synthesis 5, Theory and Applications of the Emergy Methodology*; Brown, M.T., Sweeney, S., Campbell, D.E., Huang, S.L., Ortega, E., Rydberg, T., Tilley, D.R., Ulgiati, S., Eds.; The Center for Environmental Policy, University of Florida, Gainesville, FL, USA, 2009; pp. 413–448. Presented at the 5th Biennial Emergy Research Conference, Gainesville, FL, USA, January 2008.

36. Campbell, D.E.; Lu, H.F.; Kolb, K. Emergy Evaluation of Educational Attainment in the United States. In *Emergy Synthesis 6: Theory and Applications of the Emergy Methodology*; Brown, M.T., Sweeney, S., Campbell, D.E., Huang, S.L., Ortega, E., Rydberg, T., Tilley, D.R., Ulgiati, S., Eds.; The Center for Environmental Policy, University of Florida, Gainesville, FL, USA, 2011; pp. 483–500. Presented at the 6th Biennial Emergy Research Conference, Gainesville, FL, USA, January 2010.
37. Campbell, D.E.; White, D.; Fonyo, C. Emergy of the Occupations. In *Emergy Synthesis 7: Theory and Applications of the Emergy Methodology*; Brown, M.T., Sweeney, S., Campbell, D.E., Huang, S.L., Kang, D., Rydberg, T., Tilley, D.R., Ulgiati, S., Eds.; The Center for Environmental Policy, University of Florida, Gainesville, FL, USA, 2013; pp. 381–404. Presented at the 7th Biennial Emergy Research Conference, Gainesville, FL, USA, January 2012.
38. Higgins, J.B. Emergy analysis of the Oak Openings region. *Ecol. Eng.* **2003**, *21*, 75–109.
39. Filardo, M. *Good Buildings, Better Schools*; EPI Briefing Paper #216; Economic Policy Institute: Washington, DC, USA, 2008.
40. Dober, R.P. *Campus Planning*; Reinhold Publishing Corporation: New York, NY, USA, 1962. Available online: http://www.questia.com/PM.qst?a=o&docId=54331549 (accessed on 2 April 2014).
41. Schulman, A.; Peters, C.A. GIS analysis of urban schoolyard land cover in three U.S. cities. *Urban Ecosyst.* **2008**, *11*, 65–80.
42. Energy Information Administration (EIA). Monthly Energy Review (MER)—Long-Term Historical Statistics All in One Place. Release Date: 26 February 2014. Available online: http://www.eia.gov/totalenergy/data/monthly/ (accessed on 2 April 2014).
43. Energy Information Administration (EIA). Historical Data. Available online: http://www.wou.edu/las/physci/GS361/electricity%20generation/US_consumption_1635-1945.htm (accessed on 2 April 2014).
44. Energy Information Administration. Available online: http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0209 (accessed on 2 April 2014).
45. Campbell, D.E.; Garmestani, A.S.; Hopton, M.E. Chapter 5. Emergy. In *San Luis Basin Sustainability Metrics Project: A Methodology for Evaluation Regional Sustainability*; EPA/600/R-10/182; Heberling, M.T., Hopton, M.E., Eds.; USEPA, Office of Research and Development, National Risk Management Research Laboratory: Cincinnati, OH, USA, 2010; pp. 77–162.
46. Stein, R.G. Energy cost of building construction. *Energ. Build.* **1977**, *1*, 27–29.
47. Scheuer, C.; Keoleian, G.A.; Reppe, P. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energ. Build.* **2003**, *35*, 1049–1064.
48. Arnold, A. Energy Use during Construction. Available online: http://www.google.com/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=1&ved=0CCQQFjAA&url=http%3A%2F%2Fregion5.ascweb.org%2Farnold%2520ppoint.ppt&ei=y-YYU5K7NIHM0wG064HQAg&usg=AFQjCNHzTJ1SFJFai1ey0AZzN8ASqTX-tA&bvm=bv.62577051,d.dmQ (accessed 2 April 2014).
49. Destre, G.; Levy-Garboua, L.; Sollogoub, M. Learning from experience or learning from others? Inferring informal training from a human capital earnings function with matched employer-employee data. *J. Socio-Econ.* **2008**, *37*, 919–938.

Appendix

Appendix A. Calculation of the Emergy Inputs to Each Level of the U.S. Education System

This Appendix is organized by input, so that the calculation methods, data and sources for all subsystems are discussed within each input category.

Environment

The area supporting each of the education subsystems was estimated by multiplying the average area of the school grounds by the number of schools active in a given year. The total number of schools in each subsystem was determined from data recorded in the U.S. Statistical Abstracts. Estimates for the average acreage of U.S. elementary (1 acre for 1 room and 10 acres for multi-room schools) and secondary (15 acres) schools are from [39]. Data on the average area of different types of U.S. colleges were found in [40]. The number of schools in different categories of colleges was multiplied by the average number of acres for a school of that type (61 acres for private colleges and 154 acres for public colleges) the categories were summed to estimate the total land area for colleges in the U.S. The renewable empower for the United States and the emergy of erosion [34,35] were used to quantify the emergy contributions of the environment to support the education subsystems. Total use of renewable emergy and the emergy input due to erosion were divided by the area of the nation to obtain the average empower density (semj/m^2) of environmental inputs. We assumed that 68% of the school grounds was school yard and subject to erosion based on a study by Schulman and Peters [41]. The environmental emergy contributing to each education subsystem was calculated by multiplying the school grounds area (m^2) by the renewable empower density of the U.S. and adding 0.68 times the area times the empower density of erosion.

Energy Consumed

The energy used to operate the buildings in each education subsystem was estimated using data obtained from the Energy Information Administration [42]. Statistics were available on commercial energy use in the United States from 1949 to 2011. The data were given as BTUs consumed by energy type, including, biomass, coal, petroleum, natural gas, and electricity. Longer term data on energy consumption in the U.S. from 1635 to 1945 were also found on the EIA website [43]. The area of school buildings in each subsystem from 1870 to 2011 was estimated below, under building construction. The average fraction of total commercial energy use accounted for by education in the five energy types mentioned above was given for eight years within the time period 1979 to 2003 [44]. These data were used to estimate the energy used by education buildings in each of the 5 energy types. After 1948 the emergy used in each subsystem was calculated by multiplying the average number of BTUs used, annually, within each type of energy by the fraction of the total building area accounted for by that subsystem, times 1055 J/BTU, times the transformity of the energy used. The transformities of the types of energy used in this study were: biomass, 28200 semj/J; coal, 37800 semj/J; natural gas, 43500 semj/J; petroleum, 65800 semj/J and electricity, 130500 semj/J [15,16,34]. Detailed data on education and commercial building energy use were not available prior to 1949; therefore, the average rate of energy use per square foot for education buildings from 1870 to 1948 was assumed to be similar to that calculated for 1949. Prior to 1949, the algorithm for determining the emergy of energy use was to multiply the average total energy use per sq. ft. by the fraction of that type of energy used nationally, times the area of buildings in the subsystem, times the conversion from BTUs to joules, times the transformity of the energy type. In both algorithms given above, the summation over all energy sources in a year gave the emergy used to support the buildings of the education subsystem in that year.

Building Construction

U.S. Census Bureau [29] contains estimates of the dollar value of new public and private construction put in place from 1915 to 1970. The value of public education buildings put in place was given from 1919 to 1970. In addition, the value of contracts awarded in education and science and the floor space to be built were also recorded. From these data the average cost of construction per square foot was determined. The average cost per sq. ft. was divided into the cost of public school construction put in place to estimate the area of public school buildings built in a given year. From 1993 to 2011, [29–31] give detailed data on the cost of public and private school construction. The average fraction of private to public construction costs was used to adjust the area of schools built, under the assumption that the cost for building a school was about the same regardless of the source of funds.

The value of all new construction awarded in the U.S from 1870 to 1919 was available in the U.S. Statistical Abstracts [29]. We applied the ratio of education construction to total construction in 1919 back to 1870 to estimate the value of new school construction. We applied the average cost per sq. ft. ($6.05 sq. ft.) during the relatively stable period from 1919 to 1943 to estimate the area of public education buildings constructed during that time. The area of schools built from 1870 to 2011 was partitioned into subsystems using the detailed data on public and private school construction by education level that was reported from 1993 to 2006 [29]. This information was also used to calculate the fraction of total cost that applied to each subsystem. About 14% of the construction costs were assigned to other education buildings, e.g., museums, public libraries, *etc*. and these costs were not counted as inputs to the education subsystems.

The emergy inputs to the school buildings built in each subsystem were determined using the material and labor requirements for constructing public buildings [33]. The classes of material inputs along with their emergy per unit values are as follows: (1) Minerals and raw materials including lumber and wood products, 5.18E+08 semj/g; paper, 2.15E+09 semj/g; chemicals, 2.75E+09 semj/g; petroleum refining and related products, 6.58E+04 semj/J; stone, glass, and concrete, 2.39E+09 semj/g; primary metal, 6.91E+09 semj/g (assume 2/3 steel and 1/3 aluminum); and (2) Goods including fabricated metal, 1.78E+10 semj/g; machinery except electrical, 7.76E+09 semj/g; electrical machinery, 1.46E+10 semj/g; instruments and related products, 1.46E+10 semj/g; and misc. manufactured products, 7.76E+09 semj/g. References for the specific emergies used for these materials are given in [12] and [45]. The transformity for electrical machines is a new estimate that is available from the authors on request. The same transformity was applied to instruments. The emergy of the services required for construction was calculated using the average dollar value of construction times the emergy to money ratio for the year in which the construction was put in place. The energy cost of building construction was originally taken from Stein [46], who estimated that 1.3 E+06 BTUs were required per sq. ft. built.

In this study we checked this number using data from Scheuer *et al.* [47] and [48]. The fraction of energy (336 GJ/m^2) in material placement and transport for a high rise (7) floors (0.2% of total use, [44]) was corrected by a factor of 0.217 for an average education building 2 to 3 stories [48] We used the estimate of 1.21E+6 BTU/square foot from the latter estimate in this study. This value was applied uniformly over time, using the area built to estimate energy requirements for building construction. The emergy of the energy used in construction was determined by multiplying the energy required for the area built by the fraction of energy of each type available to support building construction in that year times the transformity of the energy used. The emergy requirements for construction were summed to determine the emergy of the school buildings constructed in each year. New construction was summed to estimate the area of buildings in service at any given time after diminishing the existing area by 0.033, a factor equivalent to a 30 year replacement time. New construction put in place was assumed to come into service on the half year, thus new construction was also subject to depreciation of 0.0167 per year. The emergy lost through the depreciation of the buildings in service, given a 30 year lifetime, was assumed to be the emergy supplied by building infrastructure in support of the education process carried on by each subsystem.

Services

The total expenditures for public elementary and secondary schools from 1870 to 2011 are recorded in [28–30]. Private school expenditures were recorded in some years from 1910 to 1970, after which they were recorded annually. We used linear interpolation to fill in the missing years, and we estimated private expenses prior to 1910 assuming that private expenses on education were about 10% of the public expenses (as estimated from years when both values were known). Expenditures were divided into elementary and secondary categories based on enrollment. The dollar values of elementary and secondary expenditures minus teacher salaries were considered to be the service input to these education subsystems. Dollar values were converted to emergy using the EMR calculated in [34]. We estimated the emergy to dollar ratio of the U.S. from 1870 to 1899 for this study and we applied it to make estimates of the emergy equivalent of dollar values for the years before 1900. After 1930, college expenditures were recorded and several different aggregations were reported. For this study we used the largest measure of expenses and diminished it by the cost of teacher salaries and library operations. Library operations were added into the emergy of college/university inputs as a separate item. Before 1900 college/university expenses were not recorded, so we estimated the values for earlier years using the ratio of college/university expenses to combined elementary and secondary expenses in 1900, and extrapolated back to 1870.

New Students Entering

The average disposable income per capita in the U.S. economy in the year evaluated, times the EMR for that year [34] was used to determine the support emergy allocated to each student in all subsystems. The new students entering elementary school in the fall were estimated by adding the entering kindergarten students to the first grade students and subtracting last year's kindergarten students. Data on kindergarten and first grade enrollment were taken from [32], although these data also appear in [29–31]. The new students entering elementary school were multiplied by the emergy per capita (as determined above) to estimate the emergy supporting the students entering elementary school. Eighth graders going on to high school were estimated as ninth grade enrollment in the fall. The emergy supporting new students entering high school was calculated as for elementary students. Data on the number of students graduating from high school each year was found in the U.S. Census Bureau data [29–31]. The percent of high school graduates going on to college was given in one format from 1931 to 1979, and in another format from 1984 until 2003. Missing data from 1979 to 2003 were supplied by linear interpolation; the number of recent high school completers going on to college was given in [30,31]. A linear regression of the data set from 1931 to 2011 was used to extrapolate values back to 1870. The number of new students entering college was multiplied by the emergy per capita used for their support to determine the emergy support for newly entering college students.

Returning Students

The emergy of returning elementary students was calculated as last year's enrollment minus the eighth graders going on to high school minus dropouts. The support emergy assigned to returning students in all three subsystems was the emergy per capita calculated from disposable income, and the EMR in that year. Initially returning high school students were calculated as high school enrollment in the previous year, minus high school graduates, minus dropouts. Because of irregularities in the data we changed the method of estimating returning high school students by adjusting the number of dropouts so that enrollment of new and returning students would give the correct enrollment in a given year. We handled returning college students in a manner similar to that used for high school students, *i.e.*, high school graduates entering college, and returning students, were forced to sum to enrollment using dropouts as the adjustment factor. In some years, this implied that "Dropouts" was a positive number in the balance and thus the extra students had to matriculate from other sources, e.g., former dropouts returning to or former high school graduates entering college.

Teachers

Data on public elementary and secondary teachers have been recorded by the U.S. Census Bureau [29,30] since at least 1870 and now by ProQuest [31]. The ratio of public to private enrollment was used to estimate the total number of teachers from the number of public school teachers. The total number of teachers was separated into elementary and secondary subsystems based on elementary and secondary enrollment assuming that the student to teacher ratio was similar. Salaries for public school teachers have also been recorded since 1870. We used the salary estimates for both elementary and high school teachers and multiplied by the number of teachers and the EMR for the economy in the appropriate year to determine the emergy supporting teachers at the elementary and secondary levels. College/University teacher salaries have been recorded since 1958 [29–31]. Between 1930 and 1958 college salaries were not recorded, but we estimated them from the number of teachers and the total expenses for instruction. Prior to 1930, college teacher salaries were estimated using the ratio of college salaries to elementary and secondary salaries in 1930. The emergy supporting college teachers was determined in a manner similar to that used for elementary and secondary teachers.

Dollar Flows

The dollar flows shown in Figure 1 were taken from U.S. Census Bureau data [29]. Data on public school expenditures are complete back to 1870. Missing data on private expenditures were handled in a manner similar to that described for estimating private enrollment and teachers. Data on revenues were not quite as complete as that for expenditures. To simplify the analysis, unknown revenues were estimated from their ratio to expenditures in the closest series of years when both were known.

Emergy of Teaching and Learning

The emergy per individual at any level of education is the summation of the emergy used to keep the student in school for the period of time needed to attain that level. The average education level and years of teaching experience for elementary and secondary school teachers are given in U.S. Census Bureau data for certain years [29–31] The emergy of a teacher's education was quantified in a manner similar to that used to calculate the emergy of an individual with a given level of education, *i.e.*, by summing the required emergy inputs over the actual years that the teacher was in school, which was determined based on the average experience level of the work force at the time the data was taken.

Destre *et al.* [49] found that within 10 years workers can learn almost 100% of the new knowledge available to them after taking a new job. Based on this observation, the emergy of the teachers' experience at any time was estimated assuming that teachers learn something new about 10% of the time, while they are performing their jobs. As a result, the emergy of teachers working at any given time is the emergy of their education level determined based on the average time they spent in school, plus 10% of the emergy to support their teaching activities in a year summed over their years of experience from graduation to the present time. Thus, both the emergy of a teacher's education and experience are determined using appropriate summations over past years when they obtained their knowledge and experience. Missing data on teacher education and experience was estimated using linear interpolation between known values.

The emergy per individual that students bring to the learning process was determined similarly. A student's level of knowledge is the sum of the emergy used to support their education up to the current year. A student is still learning, so they do not also get credit for experience, since their experience is captured in their learning. In the calculation of the emergy of learning during internship and residency, we assumed that a MD would spend half of their time learning and the other half of their time doing routine work; whereas, for a postdoctoral researcher the entire time was assigned to learning.

When determining the emergy of the teaching and learning process, the emergy per individual for the students and teachers was divided by their metabolic energy use in a year and multiplied by the metabolic energy used per hour of work to give the emergy delivered per hour of participation in the teaching or learning activity. The emergy delivered per hour of work was multiplied by the hours of work (teaching and learning) and then multiplied by the number of individuals engaged in this activity to give the annual emergy of this process in a subsystem of the U.S. education system. The sum over all subsystems gives the emergy of teaching and learning in the United States as a whole in any given year.

Appendix B

Table A1. The emergy per individual for different education levels in the United States from 1870 to 2011. Numbers are in 10^{16} semj/ind. Some college means 2 years or an associate's degree, the professional degree is 3 years, and the MD degree assumes the completion of residency (5 years beyond medical school), postdoctoral experience is 2 years study beyond the Ph.D.

Year	Pre-School	Elem. Fifth Grade	Eighth Grade	High School 10–11	High School Grad.	Some College	College Grad.	Master's	Professional Degree	Doctoral Degree	MD with Internship Residency	Ph.D. with 2yr. Post Doc.
1870	7.3	28.2	38.7	46.5	54.4	75.8	97.3	118.7	129.4	140.1	NA	NA
1871	7.1	28.5	39.0	46.9	54.8	76.5	97.9	119.3	130.0	140.8	NA	NA
1872	6.9	28.8	39.2	47.7	55.2	76.5	98.2	119.6	130.4	141.1	NA	163.1
1873	6.8	28.9	39.4	47.9	55.6	77.2	98.3	119.7	130.4	141.1	NA	163.5
1874	6.6	29.0	39.5	48.0	56.3	77.0	98.8	119.8	130.5	141.2	NA	163.0
1875	6.4	29.1	39.5	48.0	56.2	77.1	98.6	119.9	130.6	141.3	NA	162.9
1876	6.3	28.8	39.4	47.9	56.3	77.9	98.3	119.9	130.2	141.0	167.3	162.6
1877	6.1	28.1	39.3	47.7	56.2	77.3	97.9	118.7	129.6	140.0	166.7	161.1
1878	6.0	27.5	39.0	47.4	56.1	76.3	96.4	117.4	128.1	139.0	165.7	159.1
1879	5.9	26.9	38.5	47.0	55.8	75.3	94.4	116.1	126.2	136.8	164.6	155.9
1880	5.9	26.3	37.7	46.5	55.5	74.2	92.5	113.6	124.5	134.6	163.3	152.7
1881	5.8	25.7	37.0	45.6	55.2	72.9	91.0	111.2	122.0	132.9	161.7	150.0
1882	5.7	25.2	36.2	44.9	54.9	72.3	89.8	109.3	119.7	130.5	160.4	147.3
1883	5.7	24.8	35.5	44.2	54.4	72.0	89.5	108.2	118.1	128.5	158.4	145.3
1884	5.5	24.5	34.9	43.5	53.6	72.1	89.9	107.7	117.3	127.2	156.6	144.5
1885	5.4	24.2	34.3	42.8	52.8	72.3	90.5	107.9	116.9	126.6	155.3	144.4
1886	5.3	23.9	33.7	42.1	52.1	71.9	90.8	108.4	117.1	126.2	153.3	144.5
1887	5.3	23.6	33.3	41.6	51.4	71.3	90.5	109.1	117.7	126.5	151.7	145.0
1888	5.3	23.4	32.9	41.3	50.8	70.7	90.1	109.5	118.5	127.1	150.7	145.7
1889	5.2	23.0	32.5	41.0	50.3	70.2	89.8	109.7	119.3	128.2	150.4	147.0
1890	5.2	22.6	32.2	40.7	49.9	70.0	89.8	109.7	119.6	129.2	150.3	148.3
1891	5.2	22.5	31.9	40.4	49.6	70.0	89.7	109.6	119.6	129.4	150.7	149.1

Table A1. *Cont.*

Year	Pre-School	Elem. Fifth Grade	Eighth Grade	High School 10–11	High School Grad.	Some College	College Grad.	Master's	Professional Degree	Doctoral Degree	MD with Internship Residency	Ph.D. with 2yr. Post Doc.
1892	5.0	22.4	31.4	39.9	49.2	69.7	89.5	109.3	119.2	129.2	151.5	149.0
1893	4.9	22.2	31.0	39.3	48.6	69.1	88.9	109.0	118.9	128.8	152.6	148.3
1894	4.8	21.9	30.7	38.6	47.9	68.4	88.3	108.7	118.6	128.6	153.3	147.8
1895	4.8	21.7	30.5	38.2	47.2	67.9	87.5	108.0	118.1	128.0	153.3	147.3
1896	4.8	21.6	30.2	37.9	46.5	66.9	86.7	107.1	117.4	127.5	152.8	146.6
1897	4.7	21.3	29.9	37.6	45.8	66.0	85.4	106.0	116.3	126.5	152.0	145.3
1898	4.6	21.0	29.7	37.0	45.3	65.0	83.8	104.5	114.7	125.0	151.1	143.5
1899	4.6	20.6	29.4	36.6	44.8	63.6	82.2	102.6	112.9	123.2	150.0	141.0
1900	4.6	20.5	28.9	36.3	44.2	62.4	80.3	100.5	110.8	121.2	148.9	138.3
1901	4.4	20.3	28.5	35.7	43.6	61.5	78.9	98.6	108.7	119.1	147.6	135.8
1902	4.7	20.2	28.3	35.3	43.3	60.7	78.3	97.1	107.2	117.3	146.0	133.8
1903	4.7	20.1	28.2	35.2	43.0	60.4	77.9	96.0	105.7	115.8	144.4	132.6
1904	5.0	22.4	31.4	39.9	49.2	69.7	89.5	109.3	119.2	129.2	151.5	149.0
1905	4.9	22.2	31.0	39.3	48.6	69.1	88.9	109.0	118.9	128.8	152.6	148.3
1891	4.8	21.9	30.7	38.6	47.9	68.4	88.3	108.7	118.6	128.6	153.3	147.8
1892	4.8	21.7	30.5	38.2	47.2	67.9	87.5	108.0	118.1	128.0	153.3	147.3
1893	4.8	21.6	30.2	37.9	46.5	66.9	86.7	107.1	117.4	127.5	152.8	146.6
1894	4.7	21.3	29.9	37.6	45.8	66.0	85.4	106.0	116.3	126.5	152.0	145.3
1895	4.6	21.0	29.7	37.0	45.3	65.0	83.8	104.5	114.7	125.0	151.1	143.5
1896	4.6	20.6	29.4	36.6	44.8	63.6	82.2	102.6	112.9	123.2	150.0	141.0
1897	4.6	20.5	28.9	36.3	44.2	62.4	80.3	100.5	110.8	121.2	148.9	138.3
1898	4.4	20.3	28.5	35.7	43.6	61.5	78.9	98.6	108.7	119.1	147.6	135.8
1899	4.7	20.2	28.3	35.3	43.3	60.7	78.3	97.1	107.2	117.3	146.0	133.8
1900	4.7	20.1	28.2	35.2	43.0	60.4	77.9	96.0	105.7	115.8	144.4	132.6
1901	5.0	22.4	31.4	39.9	49.2	69.7	89.5	109.3	119.2	129.2	151.5	149.0
1902	4.9	22.2	31.0	39.3	48.6	69.1	88.9	109.0	118.9	128.8	152.6	148.3

Table A1. *Cont.*

Year	Pre-School	Elem. Fifth Grade	Eighth Grade	High School 10–11	High School Grad.	Some College	College Grad.	Master's	Professional Degree	Doctoral Degree	MD with Internship Residency	Ph.D. with 2yr. Post Doc.
1903	4.8	21.9	30.7	38.6	47.9	68.4	88.3	108.7	118.6	128.6	153.3	147.8
1904	4.6	20.0	28.2	35.1	42.6	60.5	77.8	95.7	104.8	114.5	142.9	131.7
1905	5.1	20.2	28.2	35.2	42.5	60.4	78.6	96.0	105.0	114.2	141.4	131.5
1906	5.2	20.5	28.4	35.6	42.6	60.7	79.1	96.5	105.3	114.4	139.9	132.5
1907	5.3	21.2	28.6	35.9	42.8	61.2	79.2	97.1	105.6	114.4	138.5	133.1
1908	4.8	21.2	28.7	36.0	42.9	61.0	79.1	97.0	105.8	114.3	137.3	132.8
1909	5.1	21.4	29.0	36.0	43.0	60.7	78.8	97.0	106.0	114.9	136.8	132.7
1910	5.1	22.2	29.7	36.5	43.2	60.7	78.7	97.0	105.9	114.9	136.9	132.7
1911	5.0	22.4	29.9	37.1	43.3	61.0	78.9	97.0	106.3	115.2	137.2	133.2
1912	5.2	22.5	30.1	37.2	43.6	61.4	79.9	97.5	106.6	115.9	137.8	134.1
1913	5.3	22.1	31.0	37.5	43.8	62.2	81.1	98.6	107.7	116.7	138.8	135.6
1914	4.9	22.6	31.2	38.2	44.2	63.3	82.4	100.0	108.7	117.7	139.4	137.4
1915	5.0	22.6	31.3	38.2	44.2	63.9	83.2	101.1	109.9	118.6	139.5	138.7
1916	4.7	22.3	30.5	38.0	44.0	64.1	82.8	101.3	110.1	118.9	140.2	138.9
1917	5.6	22.7	31.3	37.4	44.9	63.1	82.5	101.7	110.7	119.5	140.6	138.5
1918	5.6	23.0	31.5	38.6	45.3	62.5	81.8	101.5	110.9	120.0	140.7	138.4
1919	5.3	22.6	31.5	38.7	45.3	63.6	80.2	100.3	110.0	119.4	140.7	138.1
1920	5.7	23.1	32.1	38.8	45.1	63.0	80.2	98.4	108.4	118.1	140.6	135.9
1921	4.9	22.7	32.1	39.2	45.6	61.9	79.2	96.5	106.6	116.5	141.0	133.1
1922	5.4	24.2	32.0	39.4	46.0	61.3	79.0	97.3	105.5	115.6	141.5	131.8
1923	6.0	24.6	32.8	40.0	46.7	62.8	79.6	97.5	106.6	114.8	141.2	131.9
1924	5.9	24.8	33.1	41.1	47.5	64.3	81.1	97.4	106.6	115.7	140.4	134.0
1925	6.0	25.8	34.9	41.3	48.3	65.0	82.6	97.9	106.6	115.8	139.4	134.2
1926	6.1	25.4	35.5	43.3	48.6	65.8	83.5	99.6	107.1	115.8	138.6	134.1
1927	6.1	26.7	35.7	43.9	49.5	66.8	84.2	101.0	108.7	116.3	137.7	134.7
1928	5.9	27.7	36.8	44.1	49.8	67.1	85.1	101.8	110.2	117.9	138.8	136.3

Table A1. *Cont.*

Year	Pre-School	Elem. Fifth Grade	Eighth Grade	High School 10–11	High School Grad.	Some College	College Grad.	Master's	Professional Degree	Doctoral Degree	MD with Internship Residency	Ph.D. with 2yr. Post Doc.
1929	6.3	27.8	36.5	45.2	51.8	67.8	85.8	102.9	111.4	119.7	139.1	138.1
1930	5.7	27.9	37.7	44.9	52.2	68.5	86.8	104.1	112.4	120.8	139.1	139.5
1931	5.0	27.7	38.3	45.4	51.9	70.8	87.1	104.4	113.3	121.6	139.4	140.6
1932	4.3	26.8	37.5	45.3	52.1	70.8	88.9	104.9	113.3	122.2	141.0	140.8
1933	4.4	26.0	36.9	44.1	50.8	70.0	88.9	105.2	114.1	122.5	142.5	140.5
1934	4.4	25.5	36.4	43.4	51.1	70.2	88.1	107.0	114.1	123.0	143.2	141.0
1935	4.6	24.1	35.5	42.8	51.3	68.9	87.8	106.5	115.7	122.8	144.0	140.9
1936	5.1	23.1	35.0	42.4	50.8	68.7	86.8	106.0	115.7	124.8	144.7	142.5
1937	5.5	22.7	35.2	42.4	50.7	69.2	87.0	106.0	115.0	124.7	144.6	142.6
1938	4.6	22.9	33.8	42.3	50.3	69.0	86.6	104.2	114.4	123.4	145.1	141.6
1939	5.1	23.2	32.9	40.9	49.9	68.2	86.3	104.3	113.2	123.3	144.9	140.8
1940	5.6	24.1	32.5	40.5	49.7	67.7	85.8	104.2	113.0	121.8	146.7	139.1
1941	5.8	25.2	33.3	40.3	50.0	67.5	85.0	103.7	112.9	121.7	146.5	139.3
1942	6.0	26.0	33.9	41.2	49.3	67.0	85.0	103.2	112.5	121.7	145.3	139.1
1943	5.4	24.9	34.6	41.5	48.3	67.5	84.5	102.5	111.9	121.2	145.4	138.7
1944	5.4	25.7	35.4	41.9	47.7	66.8	85.5	103.0	111.8	121.2	143.6	138.7
1945	5.4	26.1	35.8	42.8	48.2	66.3	84.1	101.9	111.1	119.9	142.8	137.9
1946	5.5	26.1	34.8	43.2	48.6	65.1	81.7	100.8	109.2	118.4	141.9	135.8
1947	5.7	26.3	35.8	42.4	49.6	63.6	79.3	98.4	107.8	116.1	140.4	131.5
1948	5.9	25.7	36.5	43.8	50.8	62.9	77.3	95.4	105.1	114.5	139.2	128.7
1949	5.7	26.0	36.8	44.7	51.6	63.2	76.5	93.0	102.3	112.0	137.6	125.7
1950	6.3	26.7	37.5	45.4	51.4	64.5	77.7	91.7	100.5	109.8	136.4	123.5
1951	6.1	27.4	37.1	46.5	53.0	66.1	80.0	92.0	99.7	108.4	134.9	122.9
1952	5.9	28.0	37.6	46.0	54.1	66.9	82.4	94.0	100.3	108.0	134.2	123.5
1953	6.1	28.6	38.2	46.7	54.9	69.3	83.9	97.0	102.6	109.0	132.7	125.3
1954	6.1	28.7	39.0	47.6	55.8	71.1	86.7	99.8	105.8	111.4	131.1	128.4

Table A1. *Cont.*

Year	Pre-School	Elem. Fifth Grade	Eighth Grade	High School 10–11	High School Grad.	Some College	College Grad.	Master's	Professional Degree	Doctoral Degree	MD with Internship Residency	Ph.D. with 2yr. Post Doc.
1955	6.1	29.6	39.8	48.4	55.6	72.4	88.8	101.6	108.7	114.6	130.3	132.1
1956	6.4	29.6	40.6	49.4	56.5	73.5	90.2	104.6	110.6	117.7	130.3	135.4
1957	6.4	29.8	41.0	50.5	57.6	73.5	91.7	107.1	113.9	119.9	131.5	137.8
1958	6.0	30.3	42.0	50.8	58.5	74.8	91.9	108.6	116.2	123.0	134.2	141.3
1959	6.1	30.4	41.9	51.7	59.4	76.0	93.2	110.1	117.9	125.5	137.5	143.9
1960	6.0	30.5	41.9	51.7	60.2	76.9	94.2	110.1	119.1	126.9	140.7	145.3
1961	6.0	30.9	42.5	51.7	60.5	77.7	95.1	111.5	119.4	128.4	142.8	146.7
1962	6.1	31.0	42.6	52.3	61.6	78.5	96.2	112.7	120.7	128.6	146.0	146.9
1963	6.2	30.5	42.9	52.6	61.6	79.0	96.9	113.6	122.0	130.0	148.5	148.5
1964	6.5	31.1	43.6	53.1	61.9	80.0	97.6	114.8	123.0	131.3	149.9	149.8
1965	6.9	31.5	44.2	54.2	62.9	80.2	98.4	115.3	123.8	131.9	151.3	150.5
1966	7.1	32.2	44.3	55.1	63.7	80.3	98.3	115.6	124.3	132.8	151.5	151.2
1967	7.1	33.0	45.2	55.4	64.4	81.0	98.4	116.5	124.6	133.4	152.7	151.4
1968	7.3	33.9	46.0	56.4	65.7	81.8	99.0	116.3	125.5	133.7	153.9	151.8
1969	7.6	35.2	47.0	57.5	66.8	82.5	99.8	116.5	125.4	134.6	154.9	152.6
1970	7.8	36.4	48.3	58.8	67.4	83.8	101.4	117.9	126.3	135.2	156.0	153.3
1971	8.3	37.5	49.9	60.5	68.9	85.6	102.9	119.0	127.2	135.6	156.7	154.5
1972	8.6	38.6	51.8	62.5	70.5	86.5	104.4	120.2	128.5	136.7	157.4	155.8
1973	9.3	40.1	53.9	65.0	72.5	87.7	105.8	122.2	130.0	138.3	158.6	157.0
1974	9.6	41.8	55.8	67.6	74.7	89.8	107.2	123.9	131.8	139.6	158.7	158.9
1975	8.8	42.8	56.9	69.2	76.5	92.0	108.1	124.1	132.6	140.6	159.0	160.0
1976	9.2	44.2	58.4	70.1	78.6	93.1	109.8	125.0	133.2	141.7	159.9	160.1
1977	9.4	45.2	60.1	71.9	80.7	94.3	111.3	126.4	134.1	142.4	161.3	160.2
1978	9.9	46.6	61.7	73.8	82.6	96.9	112.8	128.3	135.8	143.5	162.5	161.8
1979	10.0	47.3	63.6	75.7	84.4	99.2	115.6	130.1	137.7	145.1	163.5	163.7
1980	9.6	46.7	64.7	77.6	86.1	101.4	117.5	131.1	139.0	146.6	164.4	165.4

Table A1. *Cont.*

Year	Pre-School	Elem. Fifth Grade	Eighth Grade	High School 10–11	High School Grad.	Some College	College Grad.	Master's	Professional Degree	Doctoral Degree	MD with Internship Residency	Ph.D. with 2yr. Post Doc.
1981	9.3	47.4	65.9	78.4	87.8	102.7	118.9	133.1	139.7	147.6	164.6	165.8
1982	8.7	47.3	65.8	79.0	88.8	103.6	119.3	134.1	141.2	147.8	165.0	165.3
1983	8.6	47.3	64.5	78.5	89.9	104.5	119.7	135.0	142.1	149.2	166.2	165.9
1984	9.4	47.1	65.2	77.6	90.9	104.9	121.1	135.9	143.6	150.7	167.4	166.8
1985	9.3	46.3	65.4	78.6	92.0	106.5	121.9	136.7	144.3	152.0	168.4	168.5
1986	9.3	45.6	65.8	78.7	92.2	107.9	123.4	137.9	145.2	152.8	168.9	169.8
1987	9.6	45.1	65.7	79.4	91.5	108.8	125.1	139.1	146.7	153.9	170.9	170.8
1988	10.1	45.9	65.4	80.0	92.9	109.4	126.7	141.2	148.2	155.8	172.6	173.0
1989	10.4	47.7	65.5	80.4	94.0	109.3	127.6	143.3	150.3	157.3	174.3	175.1
1990	10.8	48.4	65.7	80.8	95.4	111.0	127.7	145.0	152.6	159.6	175.4	177.8
1991	10.2	49.0	66.6	81.0	96.0	112.3	129.3	145.9	154.0	161.6	176.7	179.9
1992	10.4	50.1	68.4	81.8	96.0	113.7	130.5	145.9	155.0	163.2	178.7	181.4
1993	10.5	51.3	69.0	83.7	96.1	114.1	132.2	147.8	155.2	164.4	180.6	182.5
1994	11.4	52.0	70.1	84.6	96.5	114.5	133.2	149.6	157.6	165.0	183.3	183.5
1995	11.7	53.0	71.6	86.2	97.9	115.3	134.4	152.0	159.7	167.7	185.9	186.8
1996	12.2	53.1	73.6	88.2	100.5	116.3	135.7	153.7	162.4	170.1	188.2	189.9
1997	12.5	54.3	74.9	90.4	101.9	118.4	137.2	155.3	164.2	173.0	190.1	193.4
1998	12.9	55.6	76.5	92.1	103.8	121.4	139.7	157.0	166.0	175.0	191.2	195.9
1999	12.6	57.5	76.9	93.9	105.8	123.2	142.8	158.6	167.6	176.6	194.2	197.9
2000	12.9	58.7	78.4	93.9	107.8	125.1	144.6	161.1	169.4	178.4	196.7	199.8
2001	12.3	59.7	79.6	95.3	109.1	127.3	146.5	164.1	171.6	179.9	199.6	201.4
2002	12.5	60.4	81.5	96.7	110.6	129.1	148.3	165.6	174.6	182.1	201.5	203.5
2003	12.6	61.0	82.7	98.8	111.0	130.1	150.2	167.5	176.2	185.2	203.3	206.2
2004	13.3	61.1	84.3	100.6	113.4	131.7	151.7	169.9	178.6	187.2	205.4	208.3
2005	13.4	62.2	85.6	102.7	115.3	132.6	153.9	172.4	181.1	189.8	207.4	211.4
2006	14.1	62.5	87.2	104.5	118.3	135.6	155.5	174.6	184.0	192.7	210.1	214.9

Table A1. *Cont.*

Year	Pre-School	Elem. Fifth Grade	Eighth Grade	High School 10–11	High School Grad.	Some College	College Grad.	Master's	Professional Degree	Doctoral Degree	MD with Internship Residency	Ph.D. with 2yr. Post Doc.
2007	12.2	63.9	88.0	106.6	120.5	138.1	158.8	177.1	186.2	195.6	213.8	218.5
2008	12.4	65.2	89.6	107.6	122.8	141.5	161.5	178.9	188.9	198.0	215.4	221.2
2009	10.5	66.0	89.0	108.2	123.5	143.9	163.5	180.8	189.0	199.1	217.8	222.5
2010	11.3	66.1	89.8	106.7	124.5	144.8	164.8	182.4	191.5	199.8	220.4	221.7
2011	11.5	66.8	90.5	107.6	124.4	144.5	166.6	185.3	193.5	202.6	217.5	223.5