Understanding of Evolution and Inheritance at KS1 and KS2: Review of literature and resources

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This bibliography is one aspect of a project designed to develop practical guidance for teaching Evolution and Inheritance at KS1 and KS2. Some findings are presented in a series of articles in the Association for Science Education's journal, *Primary Science*. In addition, the authors have produced a full report and project summary, a report on feedback from KS3-KS4 biology teachers and formative assessment probes for classroom use. All of these are available at www.nuffieldfoundation.org/primary-pupils-understanding-evolution-and-inheritance

Project remit and limits

'Evolution and Inheritance' is a potentially vast field to review, even when limited to considerations of teaching and learning in schools for the KS1-2 age range. This review of literature and resources is, therefore, selectively limited in particular ways. The target audience is those teachers and educators interested in enhancing young pupils' understanding of the science in this conceptual domain.

Our project undertook to conduct research that would inform and support the teaching and learning of Evolution and Inheritance in the National Curriculum KS1-2, a new area in the 2014 curriculum. Research with teachers set out to identify learners' difficulties and to suggest teaching and learning sequences across the 4-11 age range. Throughout, the emphasis was on 'working scientifically', promoting pupils' engagement and science discourse as the means for exchanging their evidence-based ideas. A design-based research approach ('DBR', Anderson, & Shattuck, 2012) generated, observed and recorded evidence of useful classroom strategies to inform optimal learning and teaching sequences. Formative assessment and tailored interventions could be developed collaboratively on the back of these activities (see formative assessment probes developed as outcomes of this project on the Nuffield Foundation site http://www.nuffieldfoundation.org/primary-pupils-understanding-evolution-and-inheritance . The procedures adopted ensured a sufficient quality and quantity of data to be generated from cross-sectional samples by age to describe how understandings and misunderstandings typically develop; equally importantly, we explored what management of learning experiences would be of particular relevance and value. Dissemination would use findings primarily to inform teachers' practices with the longer-term objective of facilitating and enhancing learning outcomes. In the manner of action research procedures, teachers never stepped entirely out of their conventional teaching role and the project was always mindful of how all activities might enable learning to be facilitated by using targeted interventions. These emerging messages have been published as a series of articles in the Association for Science Education's journal, 'Primary Science' (Russell and McGuigan, 2014a, 2014b, 2015a, 2015b & 2015c).

Main issues for teaching and learning

The theory of evolution is agreed by biologists and biology educators to have a necessarily central and foundational role in all students' and professionals' conceptualisation of the study of biology. Equally obvious is the fact that there have been historically, and remain, serious impediments to the *understanding* of the theory and secondly, its *acceptance*. The literature identifies three kinds of impediment:

1. The theory of evolution synthesises a huge volume and breadth of accumulated empirical data from diverse disciplines, spanning geology and palaeontology, etc.

"Despite the elegance of the theory, it is a notoriously difficult and challenging set of concepts to understand, to learn, and to teach. Some attribute this to the inherent complexity of the subject

matter. For instance, Catley, Lehrer, and Reiser (2005) argue that these challenges are symptomatic of the complex relations among micro processes of natural selection and random genetic variation, macro processes of geologic events and speciation, and their interaction—considering organisms and species as participants in ecologies distributed over space and time. These complex co-ordinations suggest the importance of designing education to support learning of central conceptual concepts throughout schooling." (Gelman & Rhodes, 2012).

Research evidence from cognitive and developmental psychology and from cognitive anthropology suggest that some predispositions in human cognitive architecture relative to the domain give rise to a 'folk biology' that favours a way of construing the living world that differs in some important respects from evolutionary ways of thinking. For example, young children may hold 'essentialist' views of living things, leading to assumptions that all individuals within the same species are identical, (Coley & Muratore, 2012; Evans, Rosengren, Lane, & Price, 2012; Gelman & Rhodes, 2012 and Shtulman & Calabi, 2012). An appreciation that there is variation between living things of the same species is important for understanding evolution. In addition, many children and students accepting the idea that organisms change may develop a belief that change is intentional and brought about because organisms *need* or *want* to change (Evans, 2008; Mull & Evans, 2010).

3. The theory of evolution is found by some to be in conflict with religious beliefs, the authority of religious texts or other socio-cultural considerations (e.g. Brem et al., 2003; Blackwell et al., 2010). It seems that the strength of feeling generated by opposing ways of thinking can be significant. Griffith and Brem (2004) report having detected clinically measurable levels of stress in some teachers when they were asked to simply think about teaching evolution.

These three categories of obstacle may be not so much discrete as interacting: the beginnings of understanding can have an impact on acceptance. For example, what is termed 'microevolution' (changes in species morphology or behaviour over relatively short periods of time in human terms) is more readily understood and accepted than macroevolution. An example might be the rapid adaptation of bacteria to antibiotics. In contrast, evolution of new species, macro-evolutionary changes over geological time that depend on interpretations of chains of complex technical evidence, are more likely to be rejected. This rejection might take the form of, 'Evolution is only a theory'. This kind of statement itself betrays a lack of understanding of the nature of scientific theory and perhaps a lack of awareness of the substantial underpinning body of factual evidence. Or it might be the result of the scientific evidence being incomprehensible to the casual recipient or so counterintuitive as not to impinge on an individual's established and habitual view of the world.

To be clear, our review and research activities were limited to exploring *understanding* of the mainstream established scientific view of evolution, not impediments to its *acceptance*. The impact of religious beliefs or alternative belief systems were not included in our activities. In a relatively small-scale project, a tight focus on science teaching and learning was necessary. It is also the case that other researchers with access to other sources of funding are actively investigating the interface between religious beliefs or creationism and evolution [http://blogs.reading.ac.uk/lasar/; http://www.templeton.org/]. In our project, participating teachers agreed to the following condition (amongst others) as defining the limits of project activity:

'Involvement in the project will require a commitment on the part of teachers to explore teaching and learning within the accepted current scientific understanding of Evolution and Inheritance. Project resources will not extend to exploring alternative views.'

Sources and structuring of literature and related resources

An initial review of research literature and informational materials useful to teachers and pupils was conducted and this continued to be refreshed throughout the project. The main sources are:

i. **Academic papers and books**

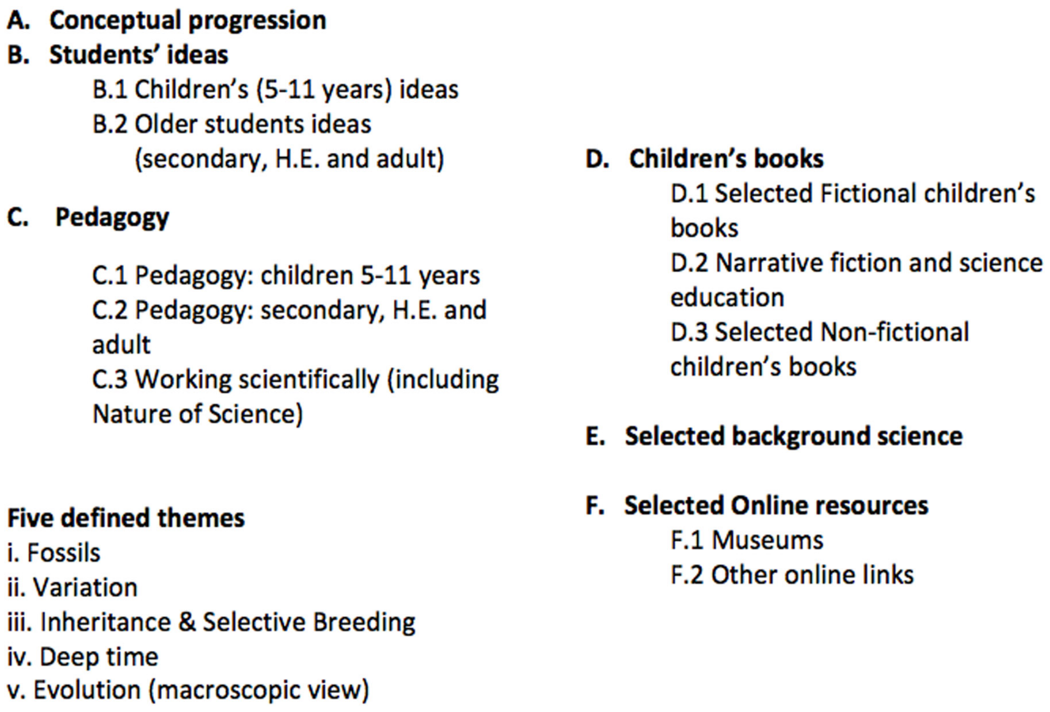
ii. **Exhibitions and museum resources**
iii. **Websites** (informational or teaching resources; learning resources for access by children)
iv. **Publications for children**

An important touchstone in framing the detail of the research was the influential 'Explore Evolution' exhibit that was developed as permanent galleries for university museums in in the Midwest and southern United States (See http://evolution.berkeley.edu/ or http://explore-evolution.unl.edu/exhibit.html, Diamond 2006.) The museum-based researchers who managed this programme structured information, repeatedly across different contexts, using a 'VIST' acronym: variation, inheritance, selection and time. Our project adopted a similar strategy but necessarily, one guided by the requirements of the national curriculum for science, manageability for teachers and access by learners. We refer to five themes: Fossils, Variation, Inheritance, Deep time and (macroscopic) Evolution. This latter categorisation guided research and classroom activities and is incorporated into the structure for this review.

Structure of the bibliography

The structure summarised below was used to organise and order relevant materials. In addition, within each of these major categories A - F, the five sub-divisions (i – v) referring to the conceptual demands that were used recurrently throughout the project are referenced, where such material exists.

Figure 1. Structure of the Bibliography and resources



A. Conceptual progression
B. Students' ideas
  B.1 Children's (5-11 years) ideas
  B.2 Older students ideas (secondary, H.E. and adult)

C. Pedagogy
  C.1 Pedagogy: children 5-11 years
  C.2 Pedagogy: secondary, H.E. and adult
  C.3 Working scientifically (including Nature of Science)

Five defined themes
i. Fossils
ii. Variation
iii. Inheritance & Selective Breeding
iv. Deep time
v. Evolution (macroscopic view)

D. Children's books
  D.1 Selected Fictional children's books
  D.2 Narrative fiction and science education
  D.3 Selected Non-fictional children's books

E. Selected background science

F. Selected Online resources
  F.1 Museums
  F.2 Other online links

The idea of **progression** (Section A) in the development of understanding was of pre-eminent interest. The fundamental issue judged to be problematic and needing empirical evidence is that of the appropriate logical and psychological sequencing of teaching and learning experiences within the domain. Consequently, this aspect is given primacy in this review by being presented and discussed first and at greatest length.

Section B, the second group of materials reviewed, is about **Students' ideas** and deals with what may broadly be described as constructivist research into science concepts relevant to the domain being explored. It is divided into younger and older age groups (the latter including teacher and other adults' ideas).

Section C, **Pedagogy,** reviews some materials that deal with teaching in the domain of Evolution and Inheritance, sub-divided into studies relevant to younger (C.1) and older (C.2) students and thirdly, consideration of 'working scientifically' (C.3) in this area of science.

A very limited and highly selective number of **children's books** is mentioned in Section D. In the case of narrative fiction (D.1), these might have been found particularly useful by participating teachers or useful to the introduction of relevant ideas. Some general principles relating to the use of narrative fiction are offered rather than any attempt at an exhaustive review of titles in section D.2, which very briefly reflects an interest that was aroused in the theoretical consideration of the role of narrative fiction in science education. The vast amount of non-fictional material available to children in their domestic and school lives is barely touched upon in Section D.3. The sheer volume of material proved too daunting and the aspiration to have teachers review possible candidates for consideration or recommendation by colleagues was squeezed out of their project involvement by the time constraints of mainstream project commitments.

Section E, **Selected background science,** can only be a gesture towards an extremely extensive set of possibilities, given the vast resources available. The same consideration applies to Section F, **Selected Online resources**, where some extremely apposite and high quality examples are mentioned. We strongly suspect more are likely to be in use by those familiar with other possibilities, nationally and internationally.

Some of the sources itemised in the review are singled out by starring as recommended for special consideration as pre-eminently significant sources. This may be because of their importance in shaping our research or for the quality of information that we would like to draw to others' attention.

The titles of works and their location within the thematic organisation of the review very frequently serve to identify the nature of their contribution. In addition, brief comments are added to many references where we have deemed this to be helpful. For example, the titles of websites are sometimes less than revealing as to their contents and they may also be multi-faceted. In the latter case, particularly useful sections are identified.

Section A. Conceptual progression

Progression

In its advice in the National Curriculum for Science, the DfE (DfE, 2013) refers to the need for progression in learning experiences (our bold font).

'**The programmes of study describe a sequence of knowledge and concepts. While it is important that pupils make progress, it is also vitally important that they develop secure understanding of each key block of knowledge and concepts in order to progress to the next stage. Insecure, superficial understanding will not allow genuine progression: pupils may struggle at key points of transition (such as between primary and secondary school), build up serious misconceptions, and/or have significant difficulties in understanding higher-order content.**' (DfE p.145)

Unfortunately, the areas of Evolution and Inheritance in the DfE's National Curriculum for Science document can be characterised as lacking a clear progression within or between key stages: the National Curriculum points towards a critically important area of study in biology while leaving barely implicit the strategic detail and essential linkages between ideas that would describe a coherent progression in learning.

How is a remedy to be found? Recent years have witnessed a massive research effort towards

conducting constructivist orientated science education research. A developmental perspective on organising pupils' curriculum experiences constitutes a further logical elaboration of this research interest. The surge in research into discrete concepts has gradually given way to the appreciation of the need for a bigger picture, a more strategic and developmental view of teaching and learning in science. It is established that constructivist research can inform a formative pedagogy that acknowledges the importance of ascertaining each learner's current understanding as a prelude to managing consequent teaching and learning experiences, (Black and Wiliam, 1990; Russell and McGuigan, 2002). The next logical step is to apply a similar thinking to curriculum development, where the research informs not just the progress of individual students but enlightens the planning and management of domains within science education over several years of study. Such a strategy is aimed at coherent teaching and learning that builds cumulatively on what can be discovered about logical and psychological progression in understanding. This interest in progression in learning has led to theorizing about and descriptions of so-called 'learning trajectories' or 'corridors' (Duschl et al., 2011). Closely associated with such pupil-centred perspectives is the practice of formative assessment – planning by teachers on the basis of sampling pupils' current understanding.
Several published studies that take an overview of progression in learners' developing understanding of Evolution and Inheritance are reviewed in some detail in this section. Any such over-arching formulations and recommendations were of particular interest in planning and interpreting our research. Our review aggregated and distilled available material with the intention of exploring the possibility of setting out a relatively smooth hypothesised progression in the main milestones. More detailed steps along the way (between milestones or particularising progression in greater detail) were informed by publications that took a focused look at particular aspects, including impediments to understanding.

The published **overview sources** that were felt to offer a significant contribution to developing a broad perspective on the teaching and learning of Evolution were:

1. The University of California Berkeley website
http://evolution.berkeley.edu/evolibrary/teach/index.php.

2. A paper by Catley, Lehrer and Reiser (2005), 'Tracing a Prospective Learning Progression for Developing Understanding of Evolution', commissioned by the National Academies Committee on Test Design for K-12 Science Achievement.

3. A chapter by Lehrer and Schauble (2012), 'Supporting enquiry about the foundations of evolutionary thinking in the elementary grades' in *The journey from child to scientist: Integrating cognitive development and the education sciences*. The chapters within the publication are based on the 37th Carnegie Symposium on Cognition (October 2009).

4. The 'Explore Evolution' museum exhibit that was developed for university museums in Kansas, Michigan, Nebraska, Oklahoma and Texas between 2005-07, with support from the National Science Foundation. (This was referred to in the U.S. press as a response to creationists and proponents of 'intelligent design'.) The construction and intensive evaluation of the exhibit are of interest in having been conducted in the informal science education sector, illustrated by contemporary research on organisms ranging from viruses to whales. In the context of the Nuffield Project's attempts to define progression through foundational concepts, the choice of four principles to be addressed repeatedly though each of seven research projects was of particular interest: variation, inheritance, selection and time, (Diamond, Evans, & Spiegel, 2012). This 'VIST' acronym is acknowledged as having been adopted from the University of Berkeley site and it is its practical implementation in the museum context is of particular interest. Three 'Overview' sections are presented below. The important significant publications relevant to the 'Explore Evolution' tend to be clustered in the volume of

papers edited by Rosengren et al., 2012, and so are mentioned individually within each relevant section of this review.

OVERVIEW ONE. The University of California at Berkeley (UCB) 'Understanding Evolution' website holds a considerable volume of information that serves to inform generally and more specifically, to support the sequenced teaching of Evolution. The site is a non-commercial, education website, teaching the science and history of evolutionary biology. It is the result of collaboration between the University of California Museum of Paleontology and the U.S. National Center for Science Education with the intention to help visitors to *'understand what evolution is, how it works, how it factors into your life, how research in evolutionary biology is performed, and how ideas in this area have changed over time'* (our italics). The site offers a large database of reliable resources for teachers and has been subjected to external evaluation.

It is very important to be clear about the status of the teaching materials and conceptual framework that informs this site and the materials accessed through it. The website was built around a conceptual framework that aims to help instructors identify a sequence of age-appropriate learning goals (K-16) to guide their teaching. An expert group of scientific and teacher advisors developed this framework at the site's inception.

The site's Understanding Evolution conceptual framework *'is aligned with the 2012 Framework for K-12 Science Education and the Next Generation Science Standards (NGSS)'*. The framework is set out in six steps: K-2 (5-7 years), grades 3-5 (8-10 years), grades 6-8) (11-13 years), grades 9-12 (14-17 years) and grades 13-16 (18-21 years). For the purposes of our study, only that sub-set of the framework that addresses K-8 is particularly germane and has been extracted as Appendix 1.

The UCB Understanding Evolution framework is set out in five sections:

1. History of Life
2. Evidence of Evolution
3. Mechanisms of Evolution
4. Nature of Science
5. Studying Evolution.

1. History of Life covers the ground of the fact that life has existed on Earth in changing forms over billions of years. Living things have diversified in a branching pattern (that we might choose to refer to as 'the Tree of Life'). This diversity has been from single celled organisms that were the ancestors of present day life forms. In some ways, those life forms in the past were very different from living things we see today, but in other ways, very similar.

Continuity of life forms by descent is to be indicated, with awareness that all life is related. Present day life forms are related to past life forms.

A link between geological change and biological evolution needs to be appreciated. The Earth's continents have changed and moved as the result of tectonic plate movement. Living things have given rise to the atmosphere on the planet, (including the oxygen we need to breathe).

Many of the life forms that once lived on Earth have become extinct - in fact, more species than are currently alive have become extinct. Extinctions are a normal part of life on Earth. Occasionally there are mass extinctions (such as the dinosaurs). Extinction of one species might open up life opportunities for another.

2. Evidence of evolution can be brought to awareness by drawing children's awareness to the changing pattern of diversity in living things over long periods of time.

The fact that plants and animals have features that allow them to survive in particular environments can be brought to learners' attention (the structure-function or form and function relationship). That fit between form and function is not always, nor need be, perfect. Some traits are not adaptive at all. An organism's features reflect its evolutionary history.

Fossils provide evidence of past living forms, the history of life on Earth. 'Transitional features' in some fossils provide evidence of how organisms changed over time. The arrangement of forms according to their depth and sequential position in the fossil record - the order in which they are found - provides information about the order in which they evolved.

There are similarities and differences between those living things currently on Earth as well as historically, between currently alive and extinct organisms.

Selective breeding can produce offspring with new traits. Selective 'artificial' breeding can also serve as a model for natural selection. People selectively breed domesticated plants and animals to produce offspring with chosen and preferred characteristics.

3. Mechanisms of Evolution. The fact of variation in a population has to be understood in order to appreciate that evolution of species by natural selection happens as a result of pressures acting on a population as a whole. Living things reproduce. Their offspring are not identical to their parents, nor to one another - they have variability (unlike clones, which some learners may have heard of either from Dolly the sheep, or the possibility of cloning pets.)

Features that help living things survive are called 'advantageous'. Depending on the environment they live in, some living things will be better adapted to survive than others. Traits that are advantageous are more likely to persist in a population because the individuals having those advantageous traits are more likely to survive and have offspring. Environmental factors or circumstances limit the number of offspring that survive to reproduce successfully. Organisms with similar requirements may compete with one another for limited resources. The more diversity within a population, the more likely the population will be able to survive environmental change.

4. The Nature of Science provides the context for the understanding of evolution. Science deals with the natural world, natural phenomena and natural processes. Learners must come to understand that the NOS accepts that scientific ideas may change, based on what is observed and experienced, that is, evidence. New evidence may give rise to new ideas and revisions of former ideas.

The natural world is explored and learned about by using our senses and measuring and other methods. Testing ideas against evidence is central and fundamental to science. Scientists use a range of different research methods (experiments, observational research, comparative research, and modeling) to collect evidence. Various techniques and instruments allow scientists to gather evidence about things that are very small, very distant in space and very distant in time.

The real process of science is complex, uses many repeated measures and can take many different forms. Accepted scientific theories survive rigorous investigation and must be supported by many lines of evidence in order to be supported.

Science is a human endeavour. (The point of this statement is probably to assert that science is socially constructed, participatory and an endeavour into which children can be inducted rather than something derived from some form of supernatural causation.)

5. Studying evolution focuses on the knowledge required to understand how the study of evolution proceeds. For younger children, the fact that scientists study fossils is pre-eminent, together with the fact that those fossils are found embedded in rocks. How and when the fossils were formed is important. That knowledge is refined as more evidence is gathered. (This is an on-going process.)

Fossils provide evidence about past life that is now extinct. Geological strata provide evidence about the age of fossils. The form of the fossilised living things (their anatomical or morphological features) provide evidence about how living things are likely to be related. Artificial selection (selective breeding of plants and animals) provides evidence about how living things can change or be changed over many generations.

Evolutionary relationships can be represented by branching trees (i.e. phylogenies or cladograms) constructed using multiple lines of evidence.

OVERVIEW TWO. Catley, Lehrer and Reiser see the topic of evolution as *'perhaps the central coordinating theory in biology, resting as it does on the foundations of disciplines including genetics, ecology and geology,'* implying that understanding evolution requires coordinating and synthesising multiple perspectives. Their contribution takes a standards or benchmark perspective. They point out that, *'Traditionally, standards describe the scientific ideas that we wish students to learn, but ideally, standards should articulate the knowledge, skills and forms of activity that students must learn in order to understand these scientific ideas. Hence, big ideas must be specified in ways that provide a window to the kinds of practices that engender their development.'* They take this idea further: *'With this expansion of standards-as-learning-performances, we undertake to illustrate how learning performances oriented around foundational concepts (big ideas) of evolution can articulate temporal sequences supporting students' long-term cognitive development.'* The concepts they identified as core to the developing understanding were *'informed by considering evolution as an explanation for how biological diversity is generated, maintained, and changed.'* Those core concepts are summarised as:

(1) Diversity at three levels: of (i) species, (ii) within species (among individuals, determined by genetic diversity) and (iii) diversity of habitats.

(2) Structure-Function form allowing functions to be performed that allow individuals to survive, 'the cornerstone of adaptation'.

(3) Ecology/Interrelationships within any particular habitat comprise a complex system. Changes affect the chance that individual organisms will survive and replicate.

(4) Variation is either random (from genetic recombination and mutation) or directed via natural selection (from mostly habitat variables), and acts to bias otherwise random genetic drift. The interplay between random and directed variation is the foundation of life's diversity.

(5) Change occurs at different scales of time and organization: microevolution refers to change in distributions of characters over comparatively brief intervals; macroevolution over longer intervals of space and time.

(6) Geologic Processes are important for comprehending and for developing hypotheses about the time-scale involved in evolution. Geologic processes are key to developing descriptions of past environments and for reconstructing the life history of the planet.

In addition to the core concepts enumerated above, Catley, Lehrer and Reiser also propose two procedural aspects or 'habits of mind' (that connect with the National Curriculum idea of 'Working Scientifically) that they regard as important:

(7) Forms of Argument *'relies on model-based reasoning and also on historic interpretation (Rudolph & Stewart, 1998). For example, geochemical processes can produce remnants of life—fossils. Historic reconstruction and comparative study of the fossil record provides evidence about continuity and* *change in species over geologic time and hence testable hypotheses about patterns of survival and extinction (Van Valkenburgh et al., 2004). At the same time, models of genetic transmission serve to account for the basic mechanism of inheritance that is the essential grist for the Darwinian mill.*'

(8) Mathematical Tools. Evolutionary processes are complex. Such complexity is managed by mathematical descriptions, including:

'*Measurement* refers to a process of assigning unit-values to an attribute. Key considerations include the nature of the unit and the nature of the scale of the unit.
Data creation refers to the process of constructing attributes and their measures, and then structuring these measures in light of a question of interest.
Distribution is a mathematical tool that structures variation. Armed with knowledge of distribution, random processes can be distinguished from directed processes.
Venn diagrams represent intersections and complements of sets of characters. These are helpful for beginning to think about likeness and difference among organisms.
Cladograms structure distributions of characters into subsets and supersets. With its emphasis on species as the units of evolutionary change, it is used to make inference about the life history of a species, the evolutionary relationships among species and groups of species (clades).'

OVERVIEW THREE. Lehrer and Schauble (2012) write: *'Collectively, we arrived at three interrelated themes that seem to be critical seeds of evolutionary reasoning: (a) variability, (b) change and (c) ecology.'* The thoughtful and extensive work of these authors includes suggested *'benchmarks of understanding'* of these three areas that are reproduced in abridged summary form as Appendix 2.

Lehrer and Schauble's Variability. Their description of progression in children's understanding of variability adopts a mathematical perspective. It starts with the description of qualitative differences in a collection of living things - fast plants, for example. Quantified observation is introduced with measurement. Those measurements are then graphed so as to make properties of the entire collection apparent. The statistics brought to bear on the graphed collection would include statistical distributions and qualities such as central tendency. Whether means or modes is not specified, but it is fairly safe to assume both are to be used, as appropriate as well as spread (range of values). Those statistics are then related explicitly to biological events or processes. The next milestone involves developing a model of the process that accounts for the distribution, evaluating the results of that model and revising the model in the light of evaluation feedback. By U.S. school grades 5-6 (age 10-11 years), the suggested milestone involves the comparison of competing models and assessing the relative fit and validity of each.

Lehrer and Schauble's Change. Approaching evolutionary change (which is by definition at the population level) by starting with change in individual organisms raises misgivings. This almost seems like an invitation to confound the two levels, individual and population. Yet Evans (2012) advocates the same starting point. In its favour, change in an individual organism, especially metamorphosis, is a strong challenge to stasis, the idea that living things in the world are unchanging. Encounters with change must be positive as stasis and essentialism would seem to be conceptually very close. In like manner, it seems to be advocated that environmental change is introduced at the local and ephemeral level of temperature, seasons and rainfall. Microenvironments might also be used to introduce the idea of change and variability within a habitat.

Lehrer and Schauble's Ecology. Ecology is the study of the interdependence of, and interactions between, living things and their physical environment. It is complex because its perspective is at the systems level. Young children's awareness will be constrained by lack of experience of this complexity, so the starting point advocated by L&S is themselves, their needs and how those needs are met in their local environment, beginning with the home. This domestic starting point can lead to thinking about the needs of other familiar animals and their 'homes' can then be studied.

Considering the distinction between the range of living things and other objects and materials that are non-living is a step into appreciating complexity. Consideration of things that were once alive is a refinement. The habitats in which living things are found can be explored by attempting to be explicit about the links between the two. What needs are met by an organism's habitat? This may initially be perceived as a one-way flow of the organism's needs being met in various ways. The shift towards an appreciation of interdependence might be prompted by asking, 'What does the living thing need and get from (take away from) its habitat and what does it add (give to other living things)?'

Interactions and interdependence can be elaborated with further detail about changing conditions included measured variables (numbers of organisms, temperature, etc.)

In summary, these studies provided an enormously helpful overview of possibilities in the field, particularly in the detailing of inter-relatedness of the various conceptual areas that must be brought together in order for a coherent understanding to be achieved. It also has to be admitted that the National Curriculum for Science in England did not aspire to such a level of detail. Furthermore, few teachers might have been anticipated to be thrilled by what we can anticipate might have been perceived as the workload implications. Nonetheless, these careful and thoughtful studies are enormously helpful in pointing the need for establishing a strategic coherence across the subject area. The pragmatics of manageability would not be overlooked by virtue of the fact that our project worked directly with pupils and teachers in the ecologically valid contexts of normal, non-specialist classrooms.

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Section B: Children's Ideas about evolution

The construction of 'personal understandings', or 'naïve theories' and their resistance to instruction has been widely reported in the alternative conceptions literature (Duit 2007). These ideas are often at odds with science explanations but as they work in everyday life, people may not be aware of discrepancies or 'mistakes' (Sinatra, 2008; Smith, 2010). Much of the constructivist research accumulated in relation to 'naïve theories' of evolution has recorded the ideas of students and adults in the secondary, HE or museum sectors (see section B.2). The current review was also able to identify a number of studies that reported the understandings of children in the 5-11 years age range. While the review was not limited to evidence from children in the primary sector (4-11 years), the evidence from research associated with this age group provided the initial insights into children's understanding and form the focus for this review.

Primary children show little understanding of the variation between species of the same kind. They tend to develop ideas of members of living things of the same kind sharing an essence or quintessential feature that makes them the same or identical (Evans, 2000; Samarapungavan & Wiers, 1997). Focusing on *within*-species similarities and differences *between* species serves children well as they begin to identify and classify living things (Evans 2008; Sinatra et al., 2008). However, while such understandings in relation to boundary classifications offer some value in terms of recognising kinds and categories, the failure to attend to within-species variation represents an obstacle to a developing awareness of evolution. Samarapungavan and Wiers, (1997) explained, '*It is likely that the lack of attention to within species variability will make it hard for many novices to restructure to Neo-Darwinian theory."* Lehrer and Schauble (2012), working with elementary children and Sandoval and Reiser (2003), working with middle school students, stress the importance of equipping students to think about individual variation as a precursor to working in natural selection.

Young children appreciate that living things reproduce organisms of the same kind. It is widely reported that children as young as 4 and 5 years appreciate that the species to which an organism belongs is fixed at birth. Children understand that 'baby' ducks hatch from the eggs laid by ducks, that they will always be ducks and that they will grow up to have the essential properties of ducks (Gelman & Wellman, 1991; Sousa et al., 2002; Astuti et al., 2004). However, commentators are uncertain as to whether this awareness of family resemblances is based on an early understanding of biological inheritance. Astuti et al., (op.cit.) explain that awareness of resemblance to the birth parent is driven by essentialist views of animal identity rather than an awareness of biological inheritance. Children involved in the Astuti study were presented with a scenario in which a baby bird emerging from a duck egg was 'adopted' by a chicken. The challenge was for children to predict the identity of the baby bird. Children correctly reasoned that the baby bird was a duck like its birth mother. Their reasoning is not attributed to a developing concept of innate potential but is thought to arise because of their essentialist beliefs that it must have already been a duck when it was born and that identity must remain constant. An emerging understanding of the inheritance of traits between parent and offspring is not recorded until children reach 6 or 7 years in North American and European samples (Springer & Keil 1989; Gimenez & Harris, 2002). Johnson and Solomon (1997) summarise the development in understanding, 'Children can understand that dogs have baby dogs before they understand that the baby is a dog *because* its birth parents were dogs. Only when children understand that birth parents pass on to their offspring the potential to become a dog and the potential to develop certain dog-like properties, have they fully fleshed out their understanding of this biological process.'

Evidence suggests that young children as well as secondary students and adults show confusion about the mechanisms of inheritance. Children (7-13 years) are reported to be unsure about characteristics that might be inherited and those that might be acquired during an organism's lifetime (Kargbo et al., 1980). On the other hand, Chin and Teou (2010) found children (10–11 years) understood that hereditary traits were transmitted via genes in the father's sperm and mother's egg. Additionally, the children demonstrated awareness that the combination of their parents' features contributed to the appearance of offspring. The gender of the offspring was thought to be related to the proportion of genes inherited from either parent. Children explained that female offspring might have 85% genes from the mother while similar proportions of genes inherited from the father were thought to result in male offspring. Some children were reported to show awareness that some information might be passed from grandparents to grandchildren. In contrast, some suggested that the traits that were inherited were an average of those in the 'mother' and 'father'. Terms such as 'DNA', 'cells', 'eggs', 'traits', 'genes', etc. were within children's vocabulary at 11 years although children were reported to be unlikely to distinguish between some of this terminology. Some of children's difficulties in distinguishing between such terms are identified in the explorations of adolescents' understanding of genetics (Lewis and Kattmann, 2010).

Primary children are thought to understand evolution as changes happening over time although they may hold misconceptions about the nature and mechanism of the change (Berti et al., 2010). These changes might be understood to take place as growth in an individual's lifetime rather than changes over generations or as metamorphosis, (Evans, 2008). Sometimes, development in features might be explained in terms of an organism's need to adapt (Ware and Gelman, 2010; Bishop & Anderson, 1990; Evans et al., 2009). For example, the long neck of the giraffe might be explained in terms of the giraffes needing to stretch their necks to reach the higher leaves. These behaviours are understood by many children to result in a gradual lengthening of the neck throughout a giraffe's life (Smith, 2010; Berti, 2010). Such changes may be thought to be inherited by the offspring. Evolution might also be explained as purposeful, orchestrated by the organism rather than as a result of an interaction between organism and the environment (Kelemen, 2004). Teleological reasoning of this kind explains evolutionary changes at the individual rather than at the population level.

Findings recorded by several studies of different age groups (Evans 2000; Berti et al., 2010; Evans 2008), suggest Darwinian theory of speciation is rarely found in amongst children. Where evolutionary reasoning was in evidence, it was almost always found to be Lamarckian in which acquired characteristics are thought to be inherited in offspring. Evans (2000) recorded only one Darwinian account and found most children explained the origin of species in terms of spontaneous generation (Evans, 2000). In their investigations of children of approximately 7-9 years, Berti et al., (2010) found initial creationist views amongst 7 year olds and mixed (creationist and evolutionary explanations) or evolutionary accounts held by 8 year olds. Evans (2008), investigating children 5-12 years, recorded the very youngest children in the sample suggesting organisms were spontaneously generated. Most 8 to 10 year olds tended to offer creationist explanation while 10–12 year olds responded in terms of creationist, mixed or evolutionary reasoning.

An understanding of Deep time is thought to require the capability to put events in temporal order and to appreciate the duration of time (Cheek, 2013). Piaget (1969) undertook some of the earliest work associated with children's understanding of time. The outcomes suggested errors in children's judgements about whether or not two events occurred successively or simultaneously. These errors were resolved as children reached about 10-11 years. Later research by Friedman (1982), described children of 4-5 years as demonstrating an awareness of both succession and duration. These children successfully sequenced events occurring over a day. Adults' accurate predictions of the timing of events were recorded for events up to two months in the past. Both older children and adults were judged to use distance-based processes that become less accurate the further back in time an event occurred. For instance, events that happened further back in time became compressed and were thought to have occurred more recently than they actually happened. Underestimations in the timing of events were associated with events occurring within the previous three years (Friedman, 2005; Janssen, Chessa, & Murre, 2006).

Evidence of young children's capabilities to successfully sequence geologic events was recorded by Trend (1998), although they displayed less success in judging the timing of these events. Teachers were reported (Trend, 2001) to exhibit similar difficulties in estimating the timing of particular events suggesting the challenge was not limited to young children. The evidence suggested that as well as experiencing difficulties with identifying the timing at which events occurred many teachers reduce geologic time to three periods: extremely ancient, moderately ancient, and more recent. Cheek argues (*op. cit.)* that understanding of Deep time and conventional time are qualitatively the same and involve the same processes. The challenge facing learners in handling Deep time tends to be associated with the magnitude of the numbers involved as these are often outside children's familiar experiences.

B1: Children's ideas (5 -11 years)

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Section C Pedagogy

We are aware of and take cognizance of the outcomes and guidance reported by research based in the context of teaching and learning of science more generally, for example, the work of Black & William, (1998) and Hattie and Timperley, (2007) who emphasise the importance of feedback for learning outcomes; also, research exploring the incorporation of argumentation techniques in the design of learning environments (Duschl & Jimenez-Aleixandre, 2012; Erduran & Jimenez-Aleixandre, 2012). However, our review focuses more specifically on evidence of pedagogical approaches that aim to support the teaching of evolution and inheritance. The accumulated research evidence seems to present a case for the introduction of ideas associated with variation, inheritance, deep time and natural selection to children in elementary and middle school (McVaugh et al., 2011). Our review summarises some of the literature associated with approaches which emphasise the importance of engaging with children's initial ideas, enquiry based approaches, 'Nature of Science' and the introduction of evidence of common ancestry to children through Tree of Life and cladogram representations.

Defining manageable conceptual categories within evolution

The central importance of evolution for understanding the history of life is widely recognised (Olson & Labov, 2012; Dobzhansky, 1973). Despite its importance, it is often considered to be difficult and an area that is most poorly understood. Obstacles to learning are attributed to ineffective teaching (Nelson 2008), the wide range of alternative conceptions (e.g. Bishop and Anderson 1990; Anderson et al., 2002; Blackwell et al., 2003). Some well-planned instructional interventions have failed according to Berti et al., (2010) or attained only modest success (e.g., Bishop & Anderson, 1990) One of the acknowledged difficulties associated with teaching and learning about evolution is the complexity and magnitude of the domain. Catley et al., (2005) are just one of a number of teams of researchers that argue that understanding evolution requires the coordination of a network of disciplines and ideas. Core concepts include diversity, structure function, ecology, variation, change and geologic processes. Evans (2008) views Variation, Inheritance, Selection and Time (the 'VIST' acronym) from the University of California Museum of Paleontology website (http://evolution.berkeley.edu*)* as core evolutionary concepts. Lehrer and Schauble (2012) define three conceptual categories important to developing evolutionary thinking: variability, change and ecology.

Engaging with initial ideas

An important thread in the examination of pedagogy within the literature is that of interactive engagement with children's and young people's evolutionary reasoning. An emphasis on initial ideas is at the heart of formative approaches that take account of understandings as an integral part of instructional design (Banet and Ayuso 2003; Nelson 2008). Berti et al., 2010) advise that ideas about evolution should be introduced to elementary children as their early initial ideas might be easier to shift than those ideas held by older children that may have become entrenched over time.

Empirical enquiries

A further challenge associated with exploring Evolution and Inheritance in real time is the intrinsic lack of opportunity to carry out empirical investigations. The importance of inquiry-based approaches is emphasised across the literature (e.g. NAS 1998; NRC. 2000; Jacobs et al., 2015). Timmerman et al., (2008) provide evidence of improved learning outcomes in the areas of evolution and biodiversity when inquiry-based approaches adopted in the university context are compared with 'traditional' laboratory activities. Inquiry-based approaches are distinguished from discovery approaches (see Furtak et al., 2012 for a discussion of definitions) and are defined by Timmerman et al., (2008) as those which take account of children's ideas and which plan project-based interventions associated with children's questions and which therefore are personally relevant. Lehrer and Schauble (2012) working within kindergarten to grade 6 suggest that knowledge of variation can be developed through in-depth, repeated investigations of the same locality that take account of children's questions and use measurement to support observation and comparison. An important feature emanating from Lehrer and Schauble's activity in schools was an approach that included 'research meetings' in which children present and critically review the evidence from their enquiries. Within a 'research meeting', students are accountable for presenting questions, the evidence for and descriptions of their claims; listeners are similarly accountable for challenging evidence and making new suggestions, etc.

Evidence based reasoning

The encouragement of evidence-based reasoning and critical thinking in the context of study of evolution is widely supported. Smith (2010) and Olson & Labov (2012) emphasised the importance of approaches that included the nature of science (NOS) for children's understanding of evolution. Within approaches that focus on NOS and science discourse, children and students use data they have gathered from observations, secondary sources, and direct enquiries as evidence in support of, or to challenge, arguments. Alters & Nelson, 2002, advocate small, group, large group and paired discussion. Asterhan and Schwarz, 2007 propose dialogical argumentation in which pairs of students put forward, justify and defend their reasoning to each other. Within NOS approaches, learners are active in the learning process (Sinatra and Pintrich, 2003). They are in control and aware of their developing understanding and can reflect on the learning process.

A number of research articles point to the importance of particular techniques in relation to developing understanding of evolution. Andersson & Wallin, 2006 emphasise the importance of attempts to make evolutionary time concrete for learners. Similarly, opportunities to handle and experience phenomena directly are recommended by Nehm & Reilly, 2007. Smith (2010), calls for investigations of variation within populations of the same species and enquiries that focus on evolution of species rather than a focus on the appearance of the first thing on Earth.

Given the relative lack of attention to phylogenetic trees in practice in formal learning, their frequency in informal learning settings and their importance for understanding the history of life we take some time to review the accumulating literature associated with children's and students' interpretation of the Tree of Life metaphor in the next section.

Tree of Life

The Tree of Life was the only sketch in Darwin's notebooks, a metaphor that describes Darwin's thinking about the interrelationships between diverse organisms and how all-living things are descended from a common ancestor. The outermost twigs represent existing species and those produced in earlier years 'represent the long succession of extinct species' (Darwin, 1859). The Tree of Life is an enduring metaphor, referred to by Novick et al., (2014) as a fundamental science construct that sets out evolutionary relationships. It is an image that summarises the focus of an enormous global research activity to assemble a comprehensive record of the relationships between all living things. Increasingly, these voluminous data sets are being represented digitally to enable access, sharing and regular updating as new evidence is found (Rosindel, & Harmon, 2012). Research into children's and adults' use of the tree metaphor and cladograms is increasingly located in the informal sector where the Tree of Life' image may feature as hard copy or in digital formats.

Despite widespread use of tree metaphors in museums, botanical gardens, zoos and online, (MacDonald and Wiley, 2012), the difficulties associated with interpreting and understanding the Tree of Life metaphor and cladograms are acknowledged in the research literature. Padian, (2008) attributes difficulties in comprehension to a lack of effective instruction and poor curriculum materials. Some difficulties are associated with lack of experience with tree representations, conceptual difficulties and misapplication of rules that might be used successfully in the context of interpreting other formats such as family trees (Ainsworth and Saffer, 2013). Novick et al., (2014) report a group of four studies (including that of Ainsworth & Saffer), that explored children's and adults' understanding as part of the 'Understanding The Tree of Life' project. These studies showed that children (9 years) could understand basic information from tree diagrams in about 10 minutes (Ainsworth and Saffer, 2013. College students performed better on tasks using the rectilinear format of tree diagrams than on the diagonal format (Catley et al., 2012). Displaying hominid evolution along a single branch seemed to lead to interpretations of hominid evolution as a linear progressive process. The position of the human (homo sapiens) in branching cladograms was also found to influence understandings of hominid evolution. For instance, representations in which the homo sapiens was positioned at the top right reinforced views of humans as the privileged species compared with representations in which the homo sapiens was centrally placed to show relationships among other taxa. Children's and adults' difficulty with understanding deep time is well recognised in the research as discussed above and Meir et al., (2007) found misunderstandings about how time is mapped onto the phylogenetic trees. Some suggested time was represented from left to right across the branch tips or from the branch tips to the root of the tree. The research of Catley and Novick, 2008 and Novick et al., (2014) recommend the inclusion of indications of time on cladograms where such data are available, to help support a sense of the time span involved. The difficulties of representing an interval rather than simply an ordinal depiction of time across the large spans are noted.

Explorations of the interactions of children with multi-touch table top interactives have revealed how novel design of interactive trees can influence engagement and understanding. Chua et al., (2013) and Davis et al., (2013) describe how some of the design features holding information about 70,000 species influenced children's collaborative exchanges and meaning making. For example, the ability to 'fly' though the different levels raised awareness of the diversity of living things while other functionality supported understanding of common descent.

The Tree of Life is an important metaphor for scientists and non-scientists, albeit one that is an over-simplification in the light of recent DNA studies. The accumulating data provides a comprehensive, dynamic resource for understanding the history of life and its continued evolution. The increasing prevalence of these tree of life representations in day-to-day life and the affordances offered by ICT for learning design suggest that the introduction of some of the basic features of the metaphor is an important aspect of teaching and learning about evolution.

C.1 Pedagogy: children 5-11 years

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Russell, T. & McGuigan, L. (2014b). How long is a piece of string? 4.5 billion years perhaps! *Primary Science* 135 Association for Science Education UK.

Russell, T. & McGuigan, L. (2015a). Why clone a sheep when they all look the same anyway? *Primary Science* 137 Association for Science Education UK.

Russell, T. & McGuigan, L. (2015b). Animals don't just grow feathers when they want to! Primary Science 138 Association for Science Education UK.

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Scharmann, L. C., Smith, M. U., James, M. C., & Jensen, M. S. (2005). Explicit reflective nature of science instruction: Evolution, intelligent design, and umbrellalogy. *Journal of Science Teacher Education, 16:27–41*.

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C.3 Working scientifically (including NOS)

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Trend, R. (2009). Commentary: Fostering students' argumentation skills in geoscience education. *Journal of Geoscience Education, 57*(4), 224-232.

Section D. Children's books

D.1 Selected children's fiction books

This very brief selection of the enormous range of titles available reflects those instances of narrative fiction that teachers in our study actually used.

Anholt, L. (2006). *Stone Girl Bone Girl: The Story of Mary Anning of Lyme Regis*. Frances Lincoln Children's Books; New Edition

Brown, R. (2013). *Ten seeds*. Pub. Andersen Press

* Campbell, E. (2011) Charlie and Kiwi: an evolutionary adventure. New York Hall of Science. Atheneum books for young readers.

Carle, E. (1997). *The tiny seed.* Puffin.

Chevalier, T. (2009) *Remarkable creatures*. Harper. (older readers)

Donaldson, M., & Scheffler, A. (2000). *Monkey puzzle.* MacMillan.

Taylor, T. (2013). *Little Changes*

Naiman, N. & McKean, D. (2003). *Wolves in the walls.* Harper Collins

* Wormell, C. (2010). *One smart fish.* Jonathan Cape.

D.2 Narrative fiction and science education

The use of narrative forms to communicate science to a general audience has been acknowledged (Avraamidou and Osborne, 2009) in the context of the public understanding of science. Fiction might serve a directly didactic purpose that helps readers to understand the natural world in a scientific manner. Using narrative fiction in a more metaphoric way may be more suited to a primary audience and is frequently used as a contextual starting point for the science primary teachers plan to introduce. Using science-relevant contexts as springboards for enquiry is well established in primary education. Blanquette and Picholle (2012) found that children were able to 'cross the gap between a literary fiction and a real-world experiment' and 'use the results of the latter to confront the predictions of the former.' Jerome Bruner discusses the complementarity in human modes of meaning making between fact and fiction, arguing that the two are distinct but complementary, 'irreducible to one another' (Bruner, 1986, p.11).

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Blanquet, E., & Picholle, E. (2012). *Inquiry based analysis of early years children's books: developing skills for later science education.* In Bruguière, C., Tiberghien, A., & Clément, P. (Eds.). (2012). E-Book Proceedings of the ESERA 2011 Conference

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Section F. Selected Online resources

F.1 Museums

www.nhm.ac.uk/nature-online/evolution Wide variety of Online resources to support teaching and learning

http://explore-evolution.unl.edu/learning.html University of Nebraska state museum site is a partnership between several museums. It highlights research into evolution and offers resources and activities aiming to support middle school students and their teachers.

* http://evolution.berkeley.edu/ University of California Berkeley offers wide ranging online support for teaching and learning about evolution

http://www.museumwales.ac.uk/cardiff/evolution-of-wales/ Exhibits support history of life in wales

* http://www.oum.ox.ac.uk/thezone/fossils/index.htm The Oxford University of natural history offers downloadable resources for teaching and learning across the Key Stages.

http://www.bristol.ac.uk/earthsciences/about/facilities/museum.html The university of Bristol museum has collections of iconic fossils on view and on line tools being developed to improve access.

F.2 Other online links

TREE OF LIFE INTERACTIVES

The accumulating information about the history of life is being assembled as digital interactives often freely available online to users in their own homes. The comprehensive information available on screen enables exploration of the relationships between the billions of different living things that have evolved since the beginning of life 3.5 billion years ago. The different digital representations offer different features and functionality. Essentially, digital interactives allow users to zoom across deep time to browse, search and make onscreen enquiries about relationships between all living things that would not be possible via a paper-based product.

http://wellcometreeoflife.org/interactive/
Wellcome foundation interactive and video.

http://timetree.org/index.php?taxon_a=HOMO+SAPIENS&taxon_b=MONKEY&submit=Search Timetreeoflife (TTOL) is a public resource led by staff at Temple University. They claim to have assembled the largest and most accurate Tree of Life by time (March 2015).

http://tolweb.org/ Tree of Life web project. The Tree of Life Web Project is a collection of information about biodiversity compiled collaboratively by hundreds of expert and amateur contributors. Its goal is to contain a page with pictures, text, and other information for every species and for each group of organisms, living or extinct. Connections between Tree of Life web pages follow phylogenetic branching patterns between groups of organisms, so visitors can browse the hierarchy of life and learn about phylogeny and evolution as well as the characteristics of individual groups.

http://www.onezoom.org/ About The OneZoom Tree of Life Explorer. OneZoom is committed to heightening awareness about the diversity of life on earth, its evolutionary history and the threats of extinction. This website allows you to explore the tree of life in a completely new way: it's like a map, everything is on one page, all you have to do is zoom in and out. OneZoom also provides free, open source, data visualisation tools for science and education, currently focusing on the tree of life. You can create visualisations of your own data as well as explore ones we have made. Got any questions or feedback? Want your data to appear here on OneZoom? just ask us. Imperial College London

http://opentree.wikispaces.com

The Open tree of life funded by the National Science Foundation assembles together all the scientific knowledge about the relationships between species. The comprehensive content is refined and updated as evidence of new species is collected. Users have control of the display of layers and can search, browse and contribute changes to the tree.

* http://terpsinoe.com/dem/homeframe.html A dynamic evolutionary map of bird evolution developed by Sonia Stephens.

http://onlinebooks.library.upenn.edu/webbin/book/lookupname?key=Owen%2C%20Richard%2C%201804-1892 Richard Owen Publications (1804 – 1892) Richard Owen's published work includes fascinating detailed illustration of his work on homologies – an invaluable source of images. Incidentally, Owen's work illustrates a distinction between the accuracy of his empirical enquiry and the now discredited theoretical interpretation of the evidence he accumulated.

* http://eol.org/info/evolution Encyclopaedia of Life (EOL), National museum of Natural History Washington US. provides learning resources which draw on the work of scientists, researchers, citizens and educationalists from around the world. New accessible learning resources which address Evolution include podcasts of the work of contemporary scientists studying evolution which are designed for classroom use.

https://lifeonearth.seas.harvard.edu/

'Harvard University in partnership with the University of Nebraska State Museum, North western University, and University of Michigan developed Life on Earth. The project team includes computer scientists, biologists, and learning researchers. Biologists from several of our partner institutions advise this project. Our partner museums include the California Academy of Sciences, the Field Museum of Natural History, the Harvard Museum of Natural History, and the University of Nebraska State Museum.' A web-based version of a Deep tree allowing exploration of the relationships between living things over 3.5 million years.

https://richarddawkins.net/

“Founded in 2006 by Richard Dawkins, the foundation’s mission is to realize Richard’s vision to remove the influence of religion in science education and public policy, and eliminate the stigma that surrounds atheism and non-belief.”

* http://evolution.berkeley.edu/evolibrary/article/evo_01 Your one-stop source for information, teaching ideas, CDP on evolution. ”What is evolution and how does it work? Evolution 101 provides the nuts-and-bolts on the patterns and mechanisms of evolution.”

http://www.ucmp.berkeley.edu/exhibit/histgeoscale.html The geologic timescale in historic perspective.

http://darwiniana.org/ This website is a project of the International wildlife museum, 4800 West Gates Pass Road, Tucson, Arizona 85745

http://www.nhm.ac.uk/kids-only/earth-space/fossil-hunting/

http://www.fossilsforkids.com/ “This website is dedicated to providing fossil education, information and fun for kids of all ages. Questions will be answered, fossils will be found and you'll have fun in the process.”

http://www.ukfossils.co.uk/ “Where to find fossils and what to find? It doesn't matter if your an experienced collector, or just starting out, our guides feature hundreds of fossil collecting locations in the UK, with geological guides, and advice. Fossils, rocks and minerals can easily be found with a little patience, we will show you how.”

http://darwin200.christs.cam.ac.uk/ This website celebrates the life, work and impact of Charles Darwin. There are lots of articles about who Darwin was, what he did and why he matters. This website has been put together by students from Christ's College, Cambridge - where Darwin studied.

https://www.geolsoc.org.uk/ “Its aims are to improve knowledge and understanding of the Earth, to promote Earth science education and awareness, and to promote professional excellence and ethical standards in the work of Earth scientists, for the public good.”

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Appendix 1. University of California Berkeley 'Understanding Evolution Conceptual Framework (Abridged K to Grade 8 only)

History of Life		
5-7 years	**8-10 years**	**11-13 years**
Life has been on Earth a long time. Life forms have changed over time	**Life has been on Earth for billions of years** Through billions of years of evolution, life forms have continued to diversify in a branching pattern, from single-celled ancestors to the diversity of life on Earth today. Life forms of the past were in some ways very different from living forms of today, but in other ways very similar. (LS4.A)	**Biological evolution accounts for diversity over long periods of time. (LS4.A, LS4.D)** Through billions of years of evolution, life forms have continued to diversify in a branching pattern, from single-celled ancestors to the diversity of life on Earth today. Life forms of the past were in some ways very different from living forms of today, but in other ways very similar. (LS4.A)
	Present-day life forms are related to past life forms. (LS4.A)	Present-day life forms are descended from past life forms; all life is related. (LS4.A)
	Geological change and biological evolution are linked Tectonic plate movement has affected the distribution and evolution of living things. (ESS1.C) Living things have had a major influence on the composition of the atmosphere and on the surface of the planet.	
Many life forms have gone extinct.	**Most species that once lived on Earth have gone extinct. (LS4.A)**	**Most species that once lived on Earth have gone extinct. (LS4.A)** Background extinctions are a normal occurrence. Mass extinctions occur. Extinction can result from environmental change. Extinction can stimulate evolution by opening up resources.

Evidence of Evolution		
5-7 years	**8-10 years**	**11-13 years**
Today there are many diverse forms of life. (LS4.D)	**Life is very diverse. (LS4.D)**	**The patterns of life's diversity through time provide evidence of evolution. (LS4.A)**
Plants and animals have features that allow them to live in various environments. (LS4.C Form is linked to function.	**There is a fit between organisms and their environments, though not always a perfect fit. (LS4.C)** Form is linked to function.	**An organism's features reflect its evolutionary history.** There is a fit between organisms and their environments, though not always a perfect fit. (LS4.C)

		There is a fit between the form of a trait and its function, though not always a perfect fit. Some traits of organisms are not adaptive
Fossils provide evidence of past life.	**Fossils provide evidence of past life. (LS4.A)**	**Fossils provide evidence of past life. (LS4.A)** The fossil record contains organisms with transitional features. The sequence of forms in the fossil record is reflected in the sequence of the rock layers in which they are found and indicates the order in which they evolved. (LS4.A)
Living things are alike in some ways and different in other ways.	**There are similarities and differences among fossils and living organisms. (LS4.A)**	**There are similarities and differences among fossils and living organisms. (LS4.A)**
	Selective breeding can produce offspring with new traits.	**Artificial selection provides a model for natural selection. (LS4.B)** People selectively breed domesticated plants and animals to produce offspring with preferred characteristics. (LS4.B)

Mechanisms of Evolution		
5-7 years	**8-10 years**	**11-13 years**
		Evolution results from natural selection acting upon variation within a population. (LS4.B)
There is variation within a population. (LS3.A, LS3.B)	**There is variation within a population. (LS3.A, LS3.B)**	**There is variation within a population. (LS3.B)** Variation is the result of genetic recombination or mutation. (LS3.A) The variation that occurs within a population is random.
Living things have offspring. (LS3.A) Offspring inherit many traits from their parents, but are not exactly the same as their parents. (LS3.A) Siblings are similar to, but not identical to, one another.	**Offspring inherit many traits from their parents, but are not exactly identical to their parents. (LS3.A, LS3.B)**	**Offspring inherit many traits from their parents, but are not identical to their parents. (LS3.B)**
	Advantageous features help living things survive. (LS4.B, LS4.C) Depending upon the environment, some living things will survive better than others. (LS4.B, LS4.C)	**Traits that are advantageous often persist in a population. (LS4.B, LS4.C)** Individual organisms with advantageous traits are more likely to survive and have offspring. (LS4.B, LS4.C) The number of offspring that survive to reproduce successfully is limited by environmental factors. (LS4.B, LS4.C) Organisms with similar requirements may compete with one another for

		limited resources. Environmental changes may provide opportunities that can influence natural selection. (LS4.B, LS4.C)

Nature of Science		
5-7 years	**8-10 years**	**11-13 years**
	Science deals with the natural world and natural explanations. (NOS8)	**Science focuses on natural phenomena and processes. (NOS8)**
Scientific ideas may change based on what we observe and experience. (NOS3)	**Scientists base their ideas on evidence from the natural world. (P3, P6, P7, NOS8)**	Scientific knowledge is open to question and revision as we come up with new ideas and discover new evidence. (P6, NOS3)
We learn about the natural world using our senses and extensions of our senses. (P3, P4, P6)	**Scientists base their ideas on evidence from the natural world. (P3, P6, P7, NOS8)**	**A hallmark of science is exposing ideas to testing. (P3, P4, P6, P7)** Scientists test their ideas using multiple lines of evidence. Scientists use multiple research methods (experiments, observational research, comparative research, and modeling) to collect evidence. (P2, P3, P4, NOS1) Scientists can test ideas about events and processes long past, very distant, and not directly observable.
	The real process of science is complex, iterative, and can take many different paths.	**The real process of science is complex, iterative, and can take many different paths.**
		Accepted scientific theories are not tenuous; they must survive rigorous testing and be supported by multiple lines of evidence to be accepted. (NOS4)
Science is a human endeavor. NOS7)	**Science is a human endeavor. NOS7**)	**Science is a human endeavor. NOS7**)

Studying Evolution		
5-7 years	**8-10 years**	**11-13 years**
		Our knowledge of the evolution of living things is always being refined as we gather more evidence.
Scientists study living things. Scientists study fossils. Scientists study rocks.	**Scientists study living things and how they are related.** Scientists study fossils and how and when they were formed. (LS4.A) Scientists study rocks and how and when they were formed.	**Scientists use multiple lines of evidence to study life over time.** Scientists use anatomical features to infer the relatedness of taxa. (LS4.A) Scientists use fossils to learn about past life. (LS4.A, ESS1.C) Scientists use geological evidence to establish the age of fossils. Scientists use artificial selection as a model to learn about natural selection. (P2)
		Classification is based on evolutionary relationships. Evolutionary relationships may be represented by branching trees (i.e. phylogenies or cladograms).

Appendix 2: Lehrer & Schauble (abridged) milestones in Progressions

Milestones in learning about variability

Milestones For Variability	Benchmarks	Detail of benchmark	Learning performance
V.1.	Difference described: Describe qualitative differences in a collection	Observe/describe/inscribe qualitative differences in a collection	Some of the leaves in this maple tree are smaller and some are larger
V.2.	Difference measured: develop or appropriate a measure and apply to a collection	Develop/appropriate a measure of an attribute and order the collection of the measure	We measured the widths of all 63 plants and arranged them from least to greatest.
V.3	Distribution: Structure a collection of measures as a distribution.	a. Display measures of an attribute in a way that makes aggregate properties of the collection visible. b. Use statistics that describe qualities of the distribution such as central tendency or spread c. Relate statistics describing distribution to biological events or processes	We graphed the number of hairs that plants had on Day 14.
V.4.	Model distributions: develop a model that accounts for the distribution observed.	a) Develop model of process accounting for distribution. b) Evaluate model results c) Propose model revision in light of model evaluation	Each plant started growth at a different time - we eventually saw a bell-shaped curve.
V.5. (Achieved by Grades 5-6, ages 10-11)	Model competition: develop competing models for the same distribution of observed values.	a) Compare competing models of observed distribution b) Develop and apply criteria for assessing relative fit and validity of competing models.	"I think the model is good if it captures the central tendency in the data. O don't care as much about whether it shows the extremes that we sometimes got."

Milestones in learning about Change in individual organisms

Milestones for Change	Benchmarks	Detail of benchmark	Learning performance
C.4.	Representational redescription of change: develop resemblance-based representations of change of particular attributes that support indirect comparison.	a) Index change in one or more attributes at two or more points in time, but via verbal/textual description or by representations intended as copies. b) Qualitatively compare one or more copy-type representation of the same continuous attribute made at different points in time c) Co-ordinate two or more representations of change described in a) and b) above.	Coloured drawings that depict changes in the colour of a rotting banana across several weeks of observation. Strips of paper representing change in height annotated with small pictures that represent first leaf, first bud, etc.
C.5.	Measures and counts: describe changes based on count or difference of one or more measured attribute.	a) Characterise change in one or more attribute as changes in counts or measures b) Characterise a measure (including units) on the basis of the selected attribute. c) Interpret change as the difference between two measurements. d) Compare net change in more than one individual and justify reasoning. e) Coordinate descriptions of change in counts or measures on two or more organisms or within attributes of the same organism	Use millimetres to record heights of a plant on different days Use a timeline to show emergence of life cycle changes. Compare change in height of different species of flowering bulbs.

C.6.	Rate: describe change as rate or changing rate.	a) Co-ordinate time elapsed with counts or measures of change, but without expressing the relationship as a rate. b) Determine rate of change by dividing the difference between two measurements of one attribute by the difference in time c) Interpret graph/table of rate of change d) Compare rates of change across more than one organism and justify reasoning e) Co-ordinate rate description with a qualitative description	"My plant grew 3mm between days 5 & 7 and then 7mm between Days * & 11. Co-ordinate rate graph with pressed plant display
C.7.	Derived or composite measure: invent derived or composite measures and use the measures to describe change.	a) Develop categories that depend on representational correspondence to measure change over time. b) Develop categories in measures that do not rely on representational correspondence and use them to measure change c) Invent a composite measure that combines other measures and use it to measure change. d) Invent a composite measure that combines and relatively weights other measures with respect to their perceived importance in the change being studied.	Use coloured paint chips to measure changes in a plant's colour over time. "Dissolved oxygen contributes more to the composite measure 'jar health' than does the number of living animals, so I will give it twice as much weight in my index for measuring changes in jar health."
C.8.	Multivariate: co-ordinate change in one measured variable with change in a second measured variable.	a) Notice/describe differing patterns of change b) Determine ratio of change in first to change in second measure relative to time	Use tables of measures of head 'height' and body height to explore the hypothesis that there is a direct relationship between changes in head size and body height as people grow from toddler to adolescent.

Milestones in learning about Ecology

Milestones For Variability	**Benchmarks**	**Detail of benchmark**	**Learning performance**
E.1.	Analogy to humans: initial criteria for life are based on overt resemblance to familiar organisms, especially people. Initial criteria for habitat are based on analogy to home.	a) Pose question: Is it alive? Where does it live? b) Judge humans and mammals as living. c) Consider places where living things are seen in their homes.	Judgments about what is alive, non-living, once alive. May anthropomorphise. Birds in nests, squirrels in trees, some carry portable shelters.
E.2.	Associate organisms with place: on the basis of direct observation, associate organisms with physical spaces that are described with respect to general location (e.g., ground, air, pond, forest, lawn)	a) Pose question: Who lives here? Where do they live? b) Make differentiations of space where organisms live.	Links between habitat and organism observed.
E.3	Organism's needs: relate organism to habitat via organism's needs and ways of satisfying those needs. The relationship is perceived to be unidirectional: the habitat satisfies needs.	a) Pose questions about needs of the organism. b) Differentiate a space as affording opportunities for providing resources to meet the needs of one or more organisms. c) Describe the advantage of macroscopic attributes that allow the organism to use the resources in a habitat. For example, these attributes might include an	What does the organism need to live? Differentiate the habitat. Observation of varied

		observable behaviour or a morphological structure. d) Develop diagnostic macroscopic attributes for identification or comparison. e) Notice that place or time may be associated with the presence or absence of particular organisms (n.b. This expands sense of place to include a potential temporal dimension.)	behaviours within the habitat. We see a lot more insect life at the pond in the afternoon than in the morning.
E.4.	Survival or organisms: consider how particular qualities of physical space, climate and time potentially affect survival of organisms or assemblages of organisms.	a) Pose questions about how particular qualities of environment affect survival.	How much sun will this plant need to flower? What is the water temperature needed to support life in this fishpond?