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A Critical Review of the Massachusetts Next Generation Science and Technology/Engineering Standards

by Stan Metzenberg, Ph.D.
Professor of Biology at California State University, Northridge

Executive Summary

The draft *Massachusetts Science and Technology/Engineering Standards*, which are for pre-Kindergarten to Grade 8 and introductory high school courses, have significant, unacceptable gaps in science content, as well as some notable errors and inaccuracies. They are stunningly devoid of Mendelian genetics and large parts of cellular biology. This is an astonishing oversight for a state that has notable institutions of higher education and a thriving biotechnology industry. The principles of evolutionary biology are also incomplete and sometimes incorrectly stated.

The standards are largely unintelligible because of abuses of the language, and sometimes grammatically incorrect. They do not support the stated purpose of standards, to indicate what students should know and be able to do. In fact, it is not certain, because of the feverish use of "action verbs" in this document, whether students will actually "know".

I recommend that the draft be withdrawn from further consideration.

Gaps in the science content

An important part of the review process is to ask whether the draft standards address the major principles and discoveries that are the foundation for each field of modern science. My finding is that these draft standards have startling gaps in the science, which cannot be resolved editorially. The gaps are so serious that any competent scientist would detect them, and if this draft were to be released publicly I think these deficiencies will be widely commented upon by the scientific community.

Stan Metzenberg is Professor of Biology at California State University, Northridge. He has 20 years' experience in university teaching in biological science. He was a Senior Science Consultant for the Academic Standards Commission in California (1998) and a State Board of Education appointee to the California Science Project (1999-2003), the California Curriculum Development and Supplemental Materials Commission (4 year term, 2003-2006) and a content review panelist for development of the California Standards Tests (1999-2010). He has recently assisted the ministries of education of Saudi Arabia (2010) and Qatar (2015) in training teacher leaders to use newly adopted science instructional materials.

POLICY BRIEF

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I will focus on biological sciences, my own area of expertise, and explain why each gap is so significant. In the teaching of biological science at the high school level, the expected components of study include cell biology (including some simple chemistry), genetics (classical and molecular), anatomy and physiology, evolutionary biology, and ecology. The *Massachusetts Science and Technology/Engineering Curriculum Framework* (October 2006) used similar descriptors for high school biology, and does not suffer from the deficiencies I am about to describe.

CELL BIOLOGY

In cell biology, it is important for students to learn the parts of the cell and their functions. These draft standards do not include any high school exposure to the nucleus, mitochondria, or chloroplasts. These are terms that are used in Clarification Statements in grade 6 (6.MS-LS1-2), and "nucleus" appears once more in a grade 8 standard (8.MS-LS3-4) in the context of the location of chromosomes, but not thereafter. No forms of the words "eukaryotic" or "prokaryotic" exist at any grade level, nor are important organelles such as "endoplasmic reticulum" or "Golgi" mentioned. The cell membrane and cell wall are only included in the aforementioned grade 6 Clarification Statement.

I understand that it is not just a matter of missing words, and that the concepts of these important cell structures and functions might be found elsewhere. I think a person defending these draft standards would point to a series of high school standards that address the cell cycle (HS-LS1-4), photosynthesis at the molecular level (HS-LS1-5), and cellular respiration (HS-LS1-7), and claim that the nucleus, chloroplast, and mitochondria are implicitly covered in each standard. However, the State Assessment Boundary on HS-LS1-4 is that "specific details of each event (e.g., steps of mitosis) are not expected in state assessment", which means that the concept of the "nucleus" could be entirely avoided during teaching. The Clarification Statements on the remaining two indicate "Emphasis is on illustrating inputs and outputs of matter…in photosynthesis by plants" and "Emphasis is on the conceptual understanding of the inputs and outputs of the process of aerobic cellular respiration", and these "clarifications" make it very clear that the chloroplast and mitochondria are unnecessary details, with the emphasis being placed on an overview of carbon cycling.

GENETICS

In genetics, I was truly astonished to see a nearly complete absence of Mendelian genetics at the high school level, despite the promising language on p.51 (titled p. 49) of the draft: "Students are able to ask questions, make and defend a claim, <u>and use concepts of probability to explain the genetic variation in a population</u>." The one place in the document where there is any suggestion of classical genetics being taught is in grade 8:

> 8.MS-LS3-4(MA). Develop and use a model to show that sexually reproducing organisms have two of each chromosome in their nucleus, and hence two variants (alleles) of each gene that can be the same or different from each other, with each chromosome acquired at random from both parents.
>
> Clarification Statements:
>
> - Examples of models can include Punnett squares, diagrams, and simulations.
> - Focus should be on dominant-recessive pattern of inheritance.

This grade 8 standard introduces the idea of alleles, which is an entry point into Mendelian genetics. The standard includes the language "with each chromosome acquired at random from both parents" that is suggestive of Mendel's Second Law, and a Clarification Statement that includes the words: "dominant-recessive pattern" suggestive of Mendel's First Law (Mendel's Third Law, related to independent assortment, is omitted at all grade levels).

However, there should be no misunderstanding: Classical Genetics is not easily absorbed as a grade 8 topic, and its near absence in the draft high school standards means that students will fail to be exposed to the ideas that revolutionized biology in the beginning of the 20th Century. The high school section titled "LS3. Heredity: Inheritance and Variation of Traits" contains three standards, the first being:

HS-LS3-1. Ask questions to clarify relationships about how DNA in the form of chromosomes is passed from parents to offspring through the processes of meiosis and fertilization in sexual reproduction.

State Assessment Boundary:

- Specific phases of meiosis or the biochemical mechanism of specific steps in the process are not expected in state assessment.

Setting aside the matter of whether "asking questions" is any way of measuring content knowledge, this standard is largely distinct from any concepts in Mendelian genetics (an expert could point out that Mendel's Second Law is implicit in the organization of chromosomes at the meiotic metaphase plate, but the State Assessment Boundary makes it clear that this is not the intent). The second standard in the LS3 section is:

HS-LS3-2. Make and defend a claim based on evidence that inheritable genetic variations may result from (a) new genetic combinations through meiosis, (b) mutations that occur during replication, and/or (c) mutations caused by environmental factors. Recognize that in general, only mutations that occur in gametes can be passed to offspring.

Clarification Statement:

- New genetic combinations through meiosis occur via the processes of crossing over and random segregation of chromosomes.

State Assessment Boundary:

- Specific phases of meiosis or identification of specific types of mutations are not expected in state assessment.

Once again this is largely separate from Mendelian genetics, although an expert would point to part (a) and the Clarification Statement as being related to Mendel's Second Law through the details of the meiotic metaphase plate (a topic proscribed by the State Assessment Boundary). A problem with this standard is the statement: "Recognize that in general, only mutations that occur in gametes can be passed to offspring". It is misleading and incorrect to write "in general", since the statement a fact and not a generality (for which there may be exceptions).

Finally, the third standard in the LS3 section is:

HS-LS3-3. Use scientific information to illustrate that genetic traits of individuals or genetic factors of a population interact with environmental factors to determine the variation and distribution of expressed traits in a population.

Clarification Statement:

- An example of the role of the environment in expressed traits in an individual can include the likelihood of developing inherited diseases (i.e., heart disease, cancer) in relation to exposure to environmental toxins and lifestyle; an example in populations can include the maintenance of the allele for sickle-cell anemia in high frequency in malaria-effected regions of the globe, such as Africa, because it confers partial resistance to malaria.

State Assessment Boundary:

- Hardy-Weinberg calculations are not expected in state assessment.

The standard is "19th Century pre-Mendelian", in the sense that it expresses the confusion in the scientific community prior to Mendel. If the "environmental factors" are interpreted through the lens of Lamarckian thought (e.g. a giraffe has a long neck because its ancestors had to stretch their necks to reach the highest branches), then students will not develop a 20th or 21st Century interpretation of heritability.

While the word "allele" in the Clarification Statement is welcome, as the second and final use of the word in the entire document, using sickle cell disease is a poor choice for several reasons. As students attempt to learn Mendelian genetics, it is important that they be given crystal clear examples that illustrate the principles of dominant and recessive traits (Mendel's First Law). The hemoglobin allele associated with sickle cell trait (HbS) is recessive in the population, except when there is a heterozygote advantage (as in the case of Plasmodium infection). It is therefore not a good teaching example for Mendel's First Law because it seemingly is recessive and dominant at the same time. Furthermore, there are many students of African descent in Massachusetts schools, a fair number of whom will themselves suffer from sickle cell disease or have parents or siblings who suffer from it, and it is cruel to draw attention to them. Africa is also a large continent, not all of which is "malaria-effected (sic)", and the malaria endemic regions of the world also include parts of Central and South America, and South Asia. I understand that the intent is to create interest by using a human genetic disorder and paired infectious disease, but the opportunity for teaching misunderstandings is great in this case. The authors would have been better to stick with more straightforward examples like Mendel's white and purple-flowered peas.

The *Massachusetts Science and Technology/ Engineering Curriculum Framework* (October 2006) does not share this deficiency with the draft standards, and admirably introduces Mendelian genetics in high school with three powerful standards:

3.4 Distinguish among observed inheritance patterns caused by several types of genetic traits (dominant, recessive, codominant, sex-linked, polygenic, incomplete dominance, multiple alleles).

3.5 Describe how Mendel's laws of segregation and independent assortment can be observed through patterns of inheritance (e.g., dihybrid crosses).

3.6 Use a Punnett Square to determine the probabilities for genotype and phenotype combinations in monohybrid crosses.

It is important to understand that by failing to adequately address Mendelian genetics in high school, students therefore cannot learn evolutionary theory in any modern sense. It was Mendel's First Law that actually explicated Darwinian theory, by showing how genetic variation could accumulate; how a heritable element could be concealed in a population, in the form of a recessive allele that gives no selective disadvantage, and not be immediately extirpated by the forces of natural selection. Mendelian theory has to be learned separately from the science of "chromosomes" and "DNA", even though there are some correlates between these subjects.

Massachusetts citizens need to have some basic understanding of Mendel's laws, because they have to make informed choices as they have families of their own. They need to understand the purpose of the Massachusetts newborn screening program, and their own risks of inherited disease; for example, a woman needs to understand that if her sister has a son with Duchenne Muscular Dystrophy (which is X-linked) that she also bears some risk of being a carrier by having possibly inherited the same deleterious X-chromosome from her mother. The exact calculation of risks is something that would be best done with the help of a Genetic Counselor, but if there is no beginning knowledge of genetics, or if the sisters don't share the same physician, then there is less chance of one being consulted.

ANATOMY AND PHYSIOLOGY

The *Massachusetts Science and Technology/ Engineering Curriculum Framework* (October 2006) includes seven standards (4.1-4.7) at the high school level to address major body systems (respectively the digestive, circulatory/excretory, respiratory, nervous, muscular/skeletal, reproductive, and endocrine systems). Unfortunately in the draft standards this critical content is boiled down to a single composite standard (HS-LS1-2) that only provides specificity in its Clarification Statements. This de-emphasis is likely to lower students' understandings of their own bodies, which may lessen their abilities as adults to speak with or understand their own physicians, or to make healthy choices in their lives.

Within Standard HS-LS1-3 there is a Clarification Statement: "…Examples could include heart rate response to exercise and recovery, insulin production and inhibition in response to blood sugar levels…" and I think it is unlikely that the authors meant to suggest "inhibition of insulin production" as a subject for study. There are hormones that do inhibit insulin production, for example somatostatin, but these would not be topics for instruction in high school. This is most likely to be a simple error by the authors.

EVOLUTION

The Massachusetts Science and Technology/ Engineering Curriculum Framework (October 2006) includes this introductory statement to the high school standards:

> "By high school, students learn the importance of Darwin's theory of evolution as a framework for explaining continuity, diversity, and change over time."

The draft standards do not include the name "Darwin" at any point in the document, which is sure to make them a target of public ridicule, and instead have this replacement:

> "Standards for Biological Evolution: Unity and Diversity help students formulate an answer to the question, "What evidence shows that different species are related?" Students construct explanations for the processes of natural selection and evolution and communicate how multiple lines of evidence support these explanations. Students can evaluate evidence of the conditions that may result in new species and understand the role of genetic variation in natural selection. Additionally, students can apply concepts of probability to explain trends in populations as those trends relate to advantageous heritable traits in a specific environment."

I understand that this is a sensitive topic, but what is proposed is not a good replacement. Part of the problem is that the draft standards do not adequately develop the basis for concepts of natural selection. A grade 7 standard in fact explicitly excludes a full discussion of the topic in the State Assessment Boundary for 7.MS-LS1-4 ("Natural selection is not expected in state assessment.") as do several grade 8 standards: 8.MS-LS1-5 ("Methods of reproduction, genetic mechanisms, gene regulation, biochemical processes, or natural selection are not expected in state assessment.") and 8.MS-LS4-4 ("Specific conditions that lead to natural selection are not expected in state assessment."). This is a tactical mistake, because natural selection is not a topic that is in the slightest way controversial. People who believe in a divine creation understand perfectly well that natural selection exists – they simply do not agree with Darwin's theory that it explains the variation of life on earth. By failing to adequately develop a non-controversial topic like natural selection, beyond an initial hint at the subject in third grade, the authors of the draft standards will make it exceedingly difficult to address the subject of Darwin's theory in later grades.

When natural selection is introduced in the context of evolution, it is in the following high school standard:

> HS-LS4-2. Construct an explanation based on evidence that the process of evolution by natural selection occurs in a population when the following conditions are met: (a) more offspring are produced than can be supported by the environment, (b) there is heritable variation among individuals, and (c) some of these variations lead to differential fitness among individuals as some individuals are better able to compete for limited resources than others.

This "when the following conditions are met" is an incorrect model for evolution by natural selection. The ecological principle of limited carrying capacity expressed in part (a) ("more offspring are produced than can be supported by the environment") is not a pre-requisite for speciation. The principle expressed in (c) ("…some individuals are better able to compete for limited resources than others") ignores differential predation as a cause of evolutionary change. Correct concepts of evolution include principles of isolation of subpopulations, in which evolutionary changes might become fixed. These isolating mechanisms could be reproductive, behavioral, or geographic (sympatric vs. allopatric speciation). Genetic bottlenecks or "founder effects" are also considered important. The authors of the draft standards would have been well served to consider Standard 5.2 of the Massachusetts Science and Technology/Engineering Curriculum Framework (October 2006), which asks students to "Describe the role that geographic isolation can play in speciation."

The next standard in the draft is the following (note that the numbering skips two - there appear to be no intervening HS-LS4-3 and HS-LS4-4):

HS-LS4-5. Evaluate the merits and limitations of a model that demonstrates how changes in environmental conditions may result in the emergence of new species over generations and/or the extinction of other species, and that these processes may occur at different rates depending on the conditions.

The introduction to this standard: "Evaluate the merits and limitations of a model…" is a poorly considered start. Students need to be educated in such a way that they understand the basis for Darwin's theory – the logic Darwin used in devising it. By failing to adequately develop the concept of natural selection, starting from Grade 6, these draft standards offer no opportunity for students to rise to the level where they are competent to even begin to "Evaluate the merits and limitations…".

The study of evolution is one area in which the lack of Mendelian genetics is most sorely felt. For example, if the draft standards were adopted, would students know that natural selection acts on the phenotype rather than the genotype of an organism? This is a core principle of the grand synthesis of Darwinian and Mendelian thought, but it is completely absent in the draft standards. The words "phenotype" and "genotype" appear in only one place, a Clarification Statement related to HS-LS1-1, but not in a way that would support student understanding of the relationship between heredity and evolution.

ECOLOGY

The draft standards have a high school section titled "LS2. Ecosystems: Interactions, Energy, and Dynamics" with seven standards. The first two relate to biotic and abiotic effects, a simple concept that could have been compressed into a single standard. They are so similar that they share two identical Clarification Statements. In a similar way, HS-LS2-3 and HS-LS2-5 cover similar ground (cycling of matter and energy) and could have been combined. They are not much of an advance compared with the way the subject is handled in Grade 5 (5-LS2-1). The remaining standards are rambling and imprecise, for example:

HS-LS2-6 Analyze data to show that in stable conditions the dynamic interactions within an ecosystem tend to maintain relatively consistent numbers and types of organisms even when small changes in conditions occur but that extreme fluctuations in conditions may result in a new ecosystem.

This is handled more clearly in Grades 6-8 of the *Massachusetts Science and Technology/Engineering Curriculum Framework* (October 2006)

17. Identify ways in which ecosystems have changed throughout geologic time in response to physical conditions, interactions among organisms, and the actions of humans. Describe how changes may be catastrophes such as volcanic eruptions or ice storms.

OTHER SUBJECTS

While I don't consider myself an expert in other fields, I will make several remarks on specific standards:

HS-PS2-1. Analyze data to support the claim that Newton's second law of motion is a mathematical model describing change in motion (the acceleration) of objects when acted on by a net force.

This is a peculiar way of addressing Newton's second law – to treat it as a "claim" rather than a settled matter. It is reminiscent of the postmodernist view that science is a social construct. It isn't clear what the intent was, but this language should be removed.

7.MS-PS2-3. Analyze data to describe the effect of distance and magnitude of electric charge on the size of electric forces.

Clarification Statement:

- Includes both attractive and repulsive forces.

State Assessment Boundary:

- State assessment will be limited to proportional reasoning.

The State Assessment Boundary is erroneous: Coulomb's law expresses an inverse square relationship between force and distance, not one that allows for "proportional" or linear reasoning.

The magnitude of electrical charge is also actually the product of charges, which do not allow for "proportional reasoning" except in the case where one of the charges is invariant.

7.MS-PS3-7(MA). Use informational text to describe the relationship between kinetic and potential energy and illustrate conversions from one form to another.

Clarification Statement:

- Types of kinetic energy include motion, sound, thermal and light; types of potential energy include gravitational, elastic, and chemical.

It was poor judgment to include "sound, thermal and light", which are too complicated to identify as "kinetic energy" with the limited knowledge of physics that these students (and teachers) will possess. The author of this Clarification Statement may want to consider how the kinetic energy equation $KE = 1/2mv^2$ can be applied to massless photons, for which $m = 0$.

The verbiage of the standards is largely unintelligible

Nearly every draft standard is written using overly complex, sometimes ambiguous or grammatically incorrect language. This greatly reduces the quality of each standard, since it then fails to be a clear communication about what the students should know and be able to do. As is the case with legal documents or pieces of legislation with inexact meanings, the difficulty is one of downstream implementation. A poorly drafted standard is likely to be ignored or misapplied, and any state-level testing on the standard will be driven by the least common denominator of its possible interpretations.

<u>Unpacking the draft standards</u>

Each standard begins with an "action" verb, such as analyze, ask, cite, communicate, construct, design, defend, develop, evaluate, make, provide, research, revise, or use. These can be compounded, for example:

"Research and communicate…"

"Make and defend…"

"Develop and use…"

"Design and evaluate…"

As the standards are imperative statements, the implied grammatical subject is the student or the reader (i.e. "[You, student,] research and communicate …")

The second clause of the standard consists of one or more object(s) of the verb, which typically are information sources (e.g. models, evidence, explanations, information, literature, questions, representations, text), that may be preceded by an adjective (e.g. informational, mathematical, qualitative). This clause can also be compounded, with "based on" or "using" or "that" as a separator, for example:

"…an explanation based on evidence that…"

"…an argument based on evidence that…"

"…evidence from literature or available data to…"

"…the claims, evidence, and reasoning behind the idea that …"

Following this verb-object pairing, a second action verb is often introduced in infinitive form, (e.g. to design, to explain, to illustrate, to predict, to relate, to show, to support), followed by a second object:

"…to support explanations that…

"…to predict and design…"

"…to relate physical properties…"

"…to describe the transfer of…"

"…to illustrate that…"

"…to clarify relationships…"

In some grammatical constructions, what would have become the object of the first verb is treated instead as a second grammatical subject, and the responsibility for the content is shifted away from the original subject (the student). This happens more frequently when the second verb is absent or not presented in infinitive form:

"Use a model that illustrates the roles of…"

(i.e. it is <u>the model</u> that is illustrating, not the student)

"Present information that illustrates how …"

(i.e. it is <u>the information</u> that is illustrating, not the student)

"Construct an explanation based on evidence that organic molecules are primarily composed of…"

"Construct and revise an argument based on evidence that the processes of photosynthesis…"

(it is not clear in either example whether the "evidence" is being provided <u>to</u> the student or <u>by</u> the student)

"Use mathematical representations to support explanations that biotic and abiotic factors affect biodiversity, including genetic diversity within a population and species diversity within an ecosystem." HS-LS2-2.

(it is not clear if the "explanations" are being provided <u>to</u> the student or <u>by</u> the student)

"Use informational text to explain that…"

(it is not clear if the "informational text" preexists, perhaps being a reading passage on an assessment item, or is to be written by the student as an exercise. If the former, then what role does the informational text play in the explaining?)

In some draft standards, a poor choice of words adds confusion about intent. In the following example, the word "that" creates ambiguity:

> "Develop and use a model to describe that structural changes to genes (mutations) may or may not result in changes to proteins, and if there are changes to proteins there may be harmful, beneficial, or neutral changes to traits." 8.MS-LS3-1.

The reader is likely to interpret the word "that" as a definite article (as in "Develop and use a model to describe *that cat on the chair*"). However, the probable intent was to use "that" as a conjunction to separate clauses (as in "Develop and use a model to describe *that all cats are mammals*").

<u>The draft standards are not a statement of what students should know</u>.

Perhaps this feverish use of action verbs in the draft standards is due to a desire among policymakers to change teaching and assessment practices. The problem is that the contortion of the language overwhelms the primary purpose of the document, to indicate what students should know and be able to do. Statements about teaching practices should be published separately, for example in the Department's document:

> An Effective Standards-Based K-12 Science and Technology/Engineering Classroom (http://www.doe.mass.edu/stem/Standards-BasedClassroom.pdf)

An alternative would be to include a separate section in the draft standards titled "What it looks like in the classroom", where such matters could be presented. This is already a prominent feature of the *Massachusetts Science and Technology/Engineering Curriculum Framework* (October 2006).

There is an underlying and I believe incorrect assumption in the draft standards, that students must "Know" the content as a prerequisite, if they can "Research and communicate" or "Evaluate" or "Model", or perform any of a dozen other "action verbs" in some way. My own experience with students is that they can do any of these things while being profoundly misled about the science, and nearly every draft standard is weakened because of this misapplication of the language. It is not reasonable to conclude that students know anything at all, if all they are being asked to do is to ask questions, as in the following example:

> HS-LS3-1. Ask questions to clarify relationships about how DNA in the form of chromosomes is passed from parents to offspring through the processes of meiosis and fertilization in sexual reproduction.

I recommend that the standards be simplified, and explicitly state what students should "Know". That is after all, the stated purpose of the standards.

Grammatical excess is not a new problem for Massachusetts

The grammatical problems I'm describing are not new to these particular draft standards, or even to older Massachusetts frameworks. The late Alan Cromer, a notable physicist who after being a student of Hans Bethe went on to establish the Physics department at Northeastern University, wrote about his experiences nearly 20 years ago:

> "State and national standards were developed by a participatory and bureaucratic process that is certain to produce incoherence, inconsistency, and grandiosity. At one point in the writing of the Massachusetts Framework it was decreed from above that each content item begin with a verb. This drove the writers to the dictionary, where they found an assortment of verbs to sprinkle in front of all their sentences. As a result, teachers and curriculum developers across the Commonwealth are forced to ponder why the Department of Education wants students to ''Investigate and describe understanding [sic] that cells have particular structures'' but to ''Compare and contrast the cell boundaries.'' Cromer (1997) *Am. J. Physics* **65**:1138

Cromer elaborated on one standard in grade 8 physical science, from the Massachusetts Department of Education, Owning the Questions Through Science and Technology Education. The Massachusetts Science and Technology Curriculum Framework, Department of Education, Malden, MA (1995):

> "For example, instead of simply stating that by eighth grade students should know that all chemical reactions involve the rearrangement of indestructible atoms, the Framework states:
>
> > Provide evidence that shows how the conservation of mass is consistent with the particulate model that describes changes in substances as the result of the rearrangement of the component particles.
>
> This statement is actually saying several things at the same time, a feature of many of the items in the Framework. Taken literally, the statement says that students are to provide evidence of a logical consistency. Since no one person could be so foolish as to have had this in mind, one can only imagine that the sentence evolved as it passed through many hands into something that sounds profound but means nothing." Cromer (1997) *Am. J. Physics* **65**:1138

What Dr. Cromer wrote in 1997 could have been written today, and it is my hope that educational policymakers will reflect upon the educational advances that have been accomplished with the *Massachusetts Science and Technology/Engineering Curriculum Framework* (October 2006), which is far superior to the draft standards that are proposed for public release.

PIONEER INSTITUTE
PUBLIC POLICY RESEARCH
185 Devonshire Street, Suite 1101, Boston, MA 02110
T: 617.723.2277 | F: 617.723.1880
www.pioneerinstitute.org