COURSE-SCALE LEARNING GOALS
E&M II

These learning goals were created by a group of physics faculty from a number of research areas, including physics education research. Rather than addressing specific content to be covered in a course (as with a syllabus), this list of broader learning goals represents what we think students should be able to *do* at this stage of their development as physicists.

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1. **Build on earlier material:** Students should deepen their understanding of introductory electromagnetism, junior-level E&M, and necessary math skills (in particular, vector calculus and differential equations).

2. **Maxwell's equations:** Students should see the various topics in the course as part of a coherent theory of electromagnetism; i.e., as a consequence of Maxwell's equations.

3. **Math/physics connection:** Students should be able to translate a description of a junior-level E&M problem into the mathematical equation(s) necessary to solve it; explain the physical meaning of the final solution, including how this is reflected in its mathematical formulation; and be able to achieve physical insight through the mathematics of a problem.

4. **Visualization:** Students should be able to sketch the physical parameters of a problem (e.g., electric or magnetic fields, and charge distributions). They should be able to use a computer program to graph physical parameters, create animations of time-dependent solutions, and compare analytic solutions with computations. Students should recognize when each of the two methods (by hand or computer) is most appropriate.

5. **Organized knowledge:** Students should be able to articulate the important ideas from each chapter, section, and/or lecture, thus indicating how they have organized their content knowledge. They should be able to filter this knowledge to access the information they'll need to solve a particular physics problem, and make connections between different concepts.

6. **Communication.** Students should be able to justify and explain their thinking and/or approach to a problem or analysis of a physical situation, in either written or oral form. Students should be able to understand and summarize a significant portion of an appropriately difficult scientific paper (e.g. an *AJP* article) on a topic from electromagnetism; and have the necessary reference skills to search for and retrieve a journal article.

7. **Problem-solving techniques:** Students should be able to choose and apply the problem-solving technique that is appropriate for a particular situation (e.g., whether to use the integral or differential forms of Maxwell's equations). They should be able to apply these methods to novel contexts (i.e., solving problems that do not map directly to examples in a textbook), indicating how they understand the essential features of the technique, rather than just the rote mechanics of its application.

   …7a. Approximations: Students should be able to effectively use approximation techniques, and recognize when they are appropriate (e.g., at points far away or very close to the source). They should be able to decide how many terms of a series expansion must be retained to find a solution of a given order, and be able to complete a Taylor Series to at least two terms.

   …7b. Symmetries: Students should be able to recognize symmetries, and be able to take advantage of them when choosing the appropriate method of solution (e.g., correctly applying the Maxwell-Ampere law to calculate the magnetic field of an infinitely long wire).

   …7c. Integration: Students should be able to write down the line, surface or volume integral required for solving a specific problem, and correctly follow through with the integration.

   …7d. Superposition: Students should recognize that – in a linear system – a general solution can be formed by the superposition of multiple components, and a specific solution found by applying appropriate boundary conditions.

8. **Problem-solving skills:** Students should be able to draw on an organized set of content knowledge (LG#5), and apply problem-solving techniques (LG#7) with that knowledge in order to carry out lengthy analyses of physical situations. They should be able to connect all the pieces of a problem to reach a final solution. They should recognize the value for learning the material of taking wrong turns, be able to recover from their mistakes, and persist in working towards a solution even though they don't necessarily see the path to that solution when they first begin the problem. Students should be able to articulate what it is that needs to be solved for in a given problem, and know when they have found it.

9. **Expecting and checking solutions:** When appropriate for a given problem, students should be able to articulate their expectations for the solution, such as the magnitude or direction of a vector field, the dependence of the solution on coordinate variables, or its behavior at large distances. For all problems, students should be able to justify the reasonableness of a solution (e.g., by checking its symmetry, looking at limiting or special cases, relating to cases with known solutions, dimensional analysis, and/or checking the scale/order of magnitude of the answer).

10. **Derivations/proofs:** Students should recognize the utility and role of formal derivations and proofs in the learning, understanding, and application of physics. They should be able to identify the necessary elements of a formal derivation or proof; and be able to reproduce important ones, including an articulation of their logical progression. They should have some facility in recognizing the range/limitations of a result based on the assumptions made in its derivation.

11. **Intellectual maturity:** Students should accept responsibility for their own learning. They should be aware of what they do and don't understand about physical phenomena and classes of problems, be able to articulate where they are experiencing difficulty, and take action to move beyond that difficulty (e.g., by asking thoughtful, specific questions).

TOPIC-SPECIFIC LEARNING GOALS
E&M II

The following list of learning goals reflects the topics and skills that were emphasized in the recent transformed E&M II courses at CU Boulder. They are organized in terms of their order of presentation in Griffiths.

Griffiths Ch 7: (Maxwell's Equations, EMF, inductance, boundary conditions)

Students should be able to:

1. …apply Stokes' Law and the Divergence theorem, and be able to use them to convert equations from differential to integral form (and vice-versa), as well as interpret the physical meaning of the resulting terms (e.g., What's a flux? What's a divergence? What does the curl tell you?)
2. …write down, and explain in words and pictures, the full set of Maxwell's Equations. This includes recognizing which are relevant for solving a given problem, and correctly using them to generate a solution. In particular, students should be able to use the integral form of Faraday's Law to determine induced electric fields; and the Maxwell-Ampere law to find induced magnetic fields.
3. …determine the total resistance or conductivity of a material for sufficiently symmetric geometries, calculate the total current flowing, and apply Ohm's Law ($\mathbf{J} = \sigma\mathbf{E}$) to relate the current density to the electric field.
4. …state the continuity equation in differential and integral forms, explain how it is an expression of charge conservation, and understand its implications in steady-state situations for quantities such as **J** and **E**.
5. …know how electromotive force is defined, and be able to compute EMF (either motional or Faraday-induced) for a variety of situations (typically with known or easily computed fields).
6. …relate mutual and self-inductance to magnetic flux and the resulting induced EMF and currents, and find the mutual and self-inductance for a situation with sufficient symmetry.
7. …set up and then solve the differential equations describing time-dependent circuit quantities (such as current, charge, voltage differences) for simple networks of resistors, capacitors, and inductors; and with AC or DC drivers.
8. …work with complex exponentials in circuit analysis (phasor diagrams), and translate between complex (imaginary) solutions and physically real quantities.
9. …calculate the total energy contained in electromagnetic fields from the energy densities, as well as compute the power and energy flow in AC circuits (by considering the energy stored in the fields, and dissipated in resistors).

10. …understand how to translate between E- and B-fields and the auxiliary fields D & H, in terms of the polarization and magnetization of a material, and be able to set up appropriate boundary conditions to determine E, B, D & H at the interface of two different media.

Griffiths Ch 8: (Conservation laws for charge, momentum & energy)

Students should be able to:

1. …physically interpret the continuity equation (LG 7.4), and be able to use the divergence theorem to express it in both integral and differential forms.
2. …recall how Poynting's theorem is derived (what assumptions go into it, and the basic mathematical manipulations), and be able to physically interpret and use **S**, along with the energy density, to solve problems involving the transfer of energy through electric and magnetic fields.
3. …qualitatively use the expression for momentum volume density, and explain its connection to conservation of momentum in EM systems (and similarly for angular momentum volume density).

Griffiths Ch 9 (9.1-9.3): (Electromagnetic waves, reflection and transmission, models for index of refraction, EM waves in conductors)

Students should be able to:

1. …construct general solutions to the wave equation, in 1-D to 3-D (including superposition solutions which might not look like the canonical "traveling wave"). For traveling waves, students should be comfortable working with the usual elements such as wavelength, wave vector, frequency and angular frequency, period, phase, polarization, and velocity.
2. …derive the traveling wave equation (and thus its solutions) in free space and in matter, starting from Maxwell's Equations. This would include deriving, understanding, and using the connections between E and B (and wave speed, wavevector, and polarization directions) as they arise from Maxwell's equations.
3. …interpret and work with plane wave solutions in complex notation, and move back and forth between this notation and the real (physical) wave formulas, as well as apply concepts from previous chapters (**S**, energy, momentum and angular momentum densities) in the context of EM plane waves.
4. …find the boundary conditions for EM waves at the interface of different media, starting from Maxwell's Equations, and apply them to solve for and interpret the reflected and transmitted waves, and their intensities (including understanding and working with the Brewster angle and Snell's Law).
5. …understand the assumptions that go into simple models for the complex index of refraction, and the associated equations for the dispersion and absorption of electromagnetic waves in dielectric and conducting media.

Griffiths Ch 10: (Potentials, gauge invariance, retarded time)

Students should be able to:

1. …compute time-dependent fields, given the scalar and vector potentials.
2. …qualitatively explain the concept and basic consequences of *gauge invariance*.
3. …understand and use the definitions of the Coulomb and Lorentz gauges, and be able to state/show how they lead to solvable wave equations.
4. …understand the meaning of *retarded time*, and compute and interpret potential functions using the retarded time formalism in cases of very simple geometry.

Griffiths Ch 11: (Radiation)

Students should be able to:

1. …identify terms in mathematical expressions that correspond to radiation fields.
2. …explain and justify both the math and physics of the “three approximations” made when calculating electric or magnetic dipole radiation.
3. …use and explain the mathematical forms of E and B for electric or magnetic dipole radiation fields, including computation or representation of energy flow, intensity and power (with angular and radial dependence).
4. …derive and use expressions for the “radiation resistance”.
5. …qualitatively describe and use the basic Larmor formula for radiation from an accelerating point charge.

Griffiths Ch 12: (Relativity)

Students should be able to:

1. …clearly describe the two principles of relativity, and their basic consequences (e.g., the relativity of simultaneity, Lorentz contraction and time dilation).
2. …use Lorentz transformations and four-vector notation to express observables in different inertial frames.
3. …know what makes a quantity *invariant* in the context of relativity, distinguish it from a *conserved* quantity, and use both concepts to compute relativistic kinematics problems.
4. …interpret and sketch space-time diagrams, and connect them to mathematical formulas.
5. …use appropriate transformations to convert electromagnetic fields and potentials between inertial frames.