While the microscopic response of magnetostrictive materials is quadratic in the magnetization $\varepsilon_{ij}^{mag} \propto m_i m_j$, understanding the macroscale response can be challenging. Figure 1a depicts a series of three magnetostriction curves for a positive magnetostrictive material (e.g., Galfenol). For each curve, a static bias stress is applied to the material, after which a magnetic field is applied and the resulting strain is schematically illustrated. The field and stress are assumed parallel to each other. Note all three curves have been shifted to read zero strain at zero magnetic field. This is a common convention in the literature. While this shift nominally removes the deformation caused by the mechanical load, a downside is that it also negates the zero-field magnetostriction due to magnetic domain reorientation. This can be problematic as the ΔE effect has been observed to be most pronounced at zero-field.

Figure 1b depicts the domain evolution for a material in tension (red line). At zero field (state b1) the magnetic domains preferentially align parallel to the axis of the applied load due to magnetoelastic anisotropy. Since magnetostriction causes elongation parallel to the magnetization, each domain elongates parallel to the stress direction as well. As the magnetic field is applied (b_2 - b_4) 180° domain wall motion occurs with domains parallel to the field growing, and those opposite the field shrinking. Even though the net magnetization increases, there is *negligible magnetostriction* due to the domain wall motion. While locally the magnetostriction is quadratic in the magnetization, clearly macroscale magnetostriction does not need to exhibit a quadratic dependence on the *net* magnetization.

Figure 1c depicts the domain evolution for a material in compression (blue line). At zero field (state c_1) the magnetic domains align orthogonal to the axis of the applied load due to magnetoelastic anisotropy. This causes a magnetostrictive elongation perpendicular to the stress, and parallel contraction (i.e., to conserve volume). As the magnetic field is applied, each domain undergoes a 90° rotation, with corresponding elongation parallel to the field, and perpendicular contraction. As a result, between zero-field (c_1) and saturation (c_4), the material elongates $\frac{3}{2}\lambda_s$ in the field direction,

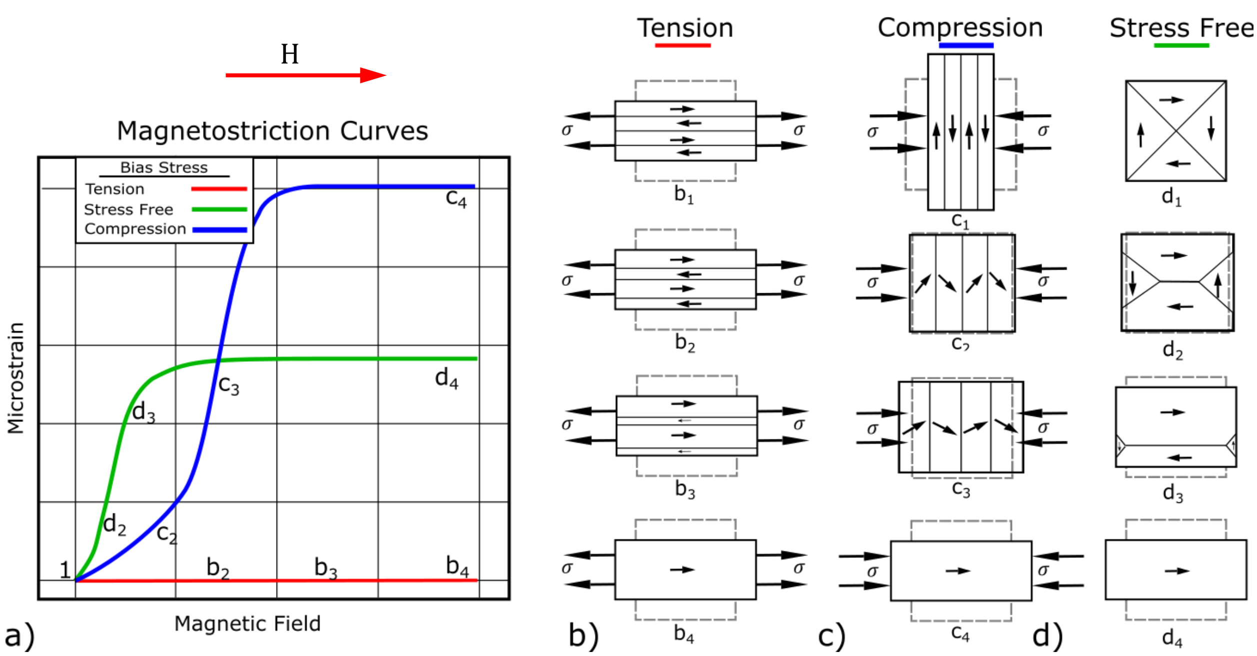

Figure 1: a) Three magnetostriction curves plotted vs magnetic field. b-d): Domain evolution due to the combined mechanical and magnetic loading.

where λ_s is the saturation magnetostriction. A full λ_s is due to the magnetization finishing parallel to the field, while $\frac{1}{2}\lambda_s$ is due to the initial contraction due to the domains aligning orthogonal to the stress / field axis.

Figure 1d depicts the domain evolution for an unloaded (stress-free) material (green line). For a material with small magnetocrystalline anisotropy, the zero field domains (state d_1) will be randomly arranged such that the net magnetization is zero (or very small). As the magnetic field is applied (d_2 – d_3), the domains parallel to the field grow due to domain wall motion, with all other domains shrinking. After a large enough field is applied (d_4), a single domain appears parallel to the field. During this process the observed magnetostriction will be roughly λ_s, however the actual measurement will be very sensitive to initial domain configuration.

Based on these examples, we see that some care must be given when analyzing data from materials large enough for multiple domains to coexist. This also shows that if we wish to measure λ_s we can't simply apply a magnetic field to a material until it saturates (we could measure anything from zero magnetostriction through $\frac{3}{2}\lambda_s$!). The most common way to measure λ_s is to first apply a magnetic field in one direction to magnetic saturation, and then apply a saturating field in a perpendicular direction. By taking the difference in strain measurements between the perpendicular saturated states, you will obtain $\frac{3}{2}\lambda_s$. This is conceptually similar to what's shown in Figure 1c, but can be done without an apparatus to load the material. Furthermore, by simultaneously recording the net magnetization of the material, you can guarantee that saturation is reached, while it would be very challenging to guarantee your material is in the anti-parallel domain configuration of c_1, compared to the canted configuration in c_2.