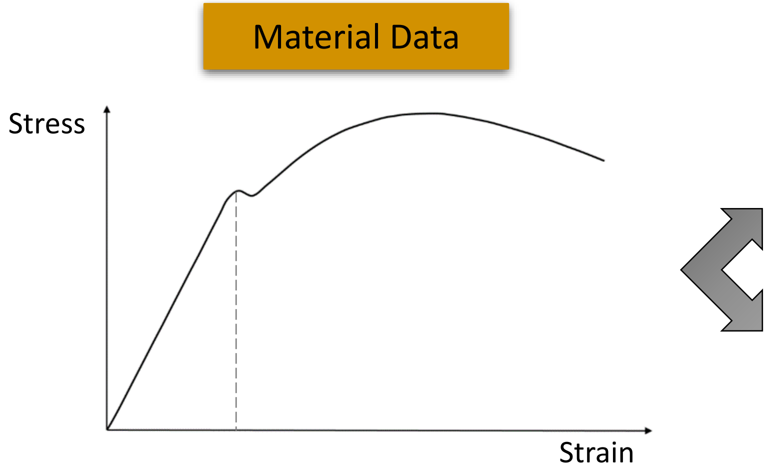
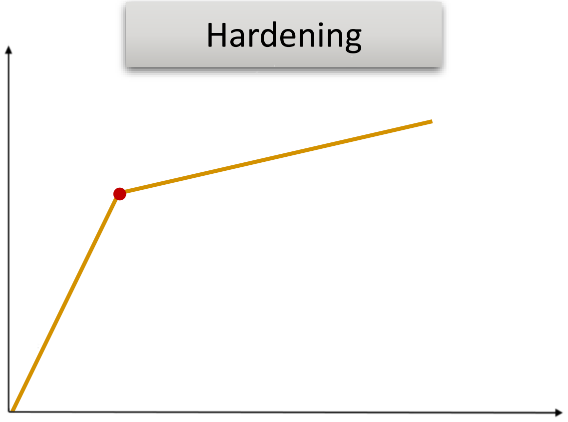
Hardening of Plasticity

Metal Plasticity – Lesson 3

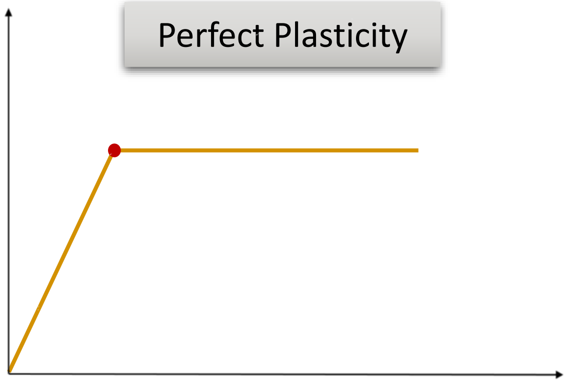
Metal Plasticity: Hardening

We discussed yield criteria before. What will happen after the stress status reaches the yield surface? Does material still have further strength after yielding ?





- Material's strength continues to grow, but with smaller slope. The hardening part of plasticity can be approximated by linear, piece-wise linear or high-order functions.

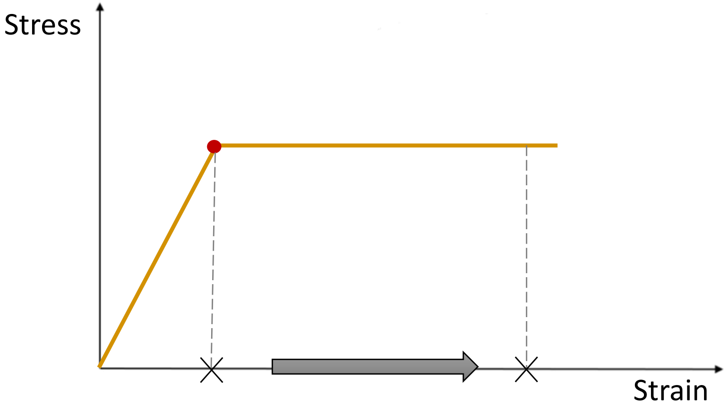


- Material's strength stops growing once the yield surface is reached.

Metal Plasticity: Perfect Plasticity

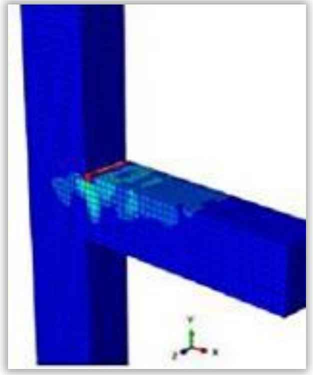
Almost all materials have a certain level of hardening. For perfect plasticity, engineers intentionally ignore any increase of strength after entering plasticity. This leads to more conservative design and analysis results.

- Once a material point reaches the yield surface, theoretically, any small increment of load can cause an infinitely large deformation.



Strain jumps without any load increment

- In simulation of a body, when a certain material point reaches plasticity and loses resistance to any further load, the neighboring material points, which haven't yielded, will share the load and prevent excessive distortion.

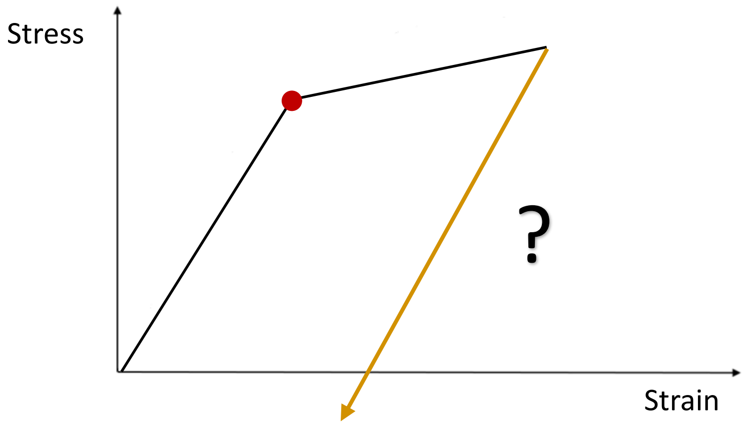


Metal Plasticity: Isotropic and Kinematic Hardening

In a 1D illustration, we can see that the hardening part can be approximated by a single linear function, piece-wise linear function or high-order functions. Here we will use a single linear function to discuss hardening. We call it bilinear hardening. Next, we will try to answer the two questions below.

1. For the 1D plasticity illustration, what will happen if we unload the material and continue to load in the opposite direction (cyclic loading)?

2. In 3D, how does a yield surface develop for hardening?

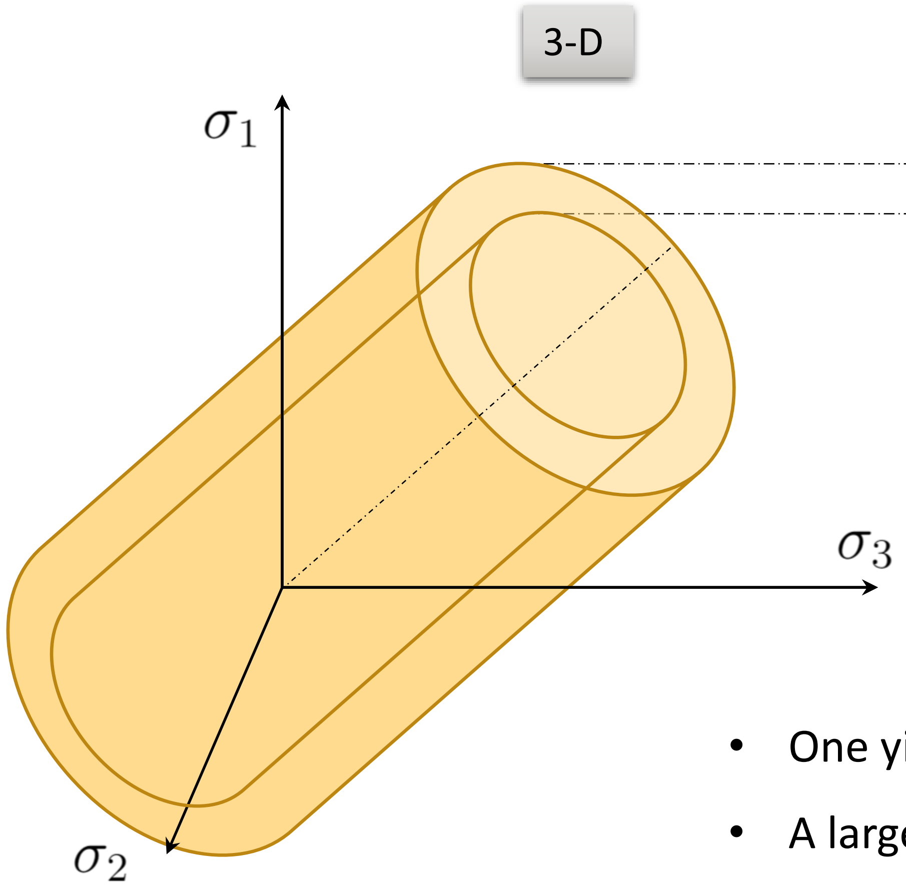


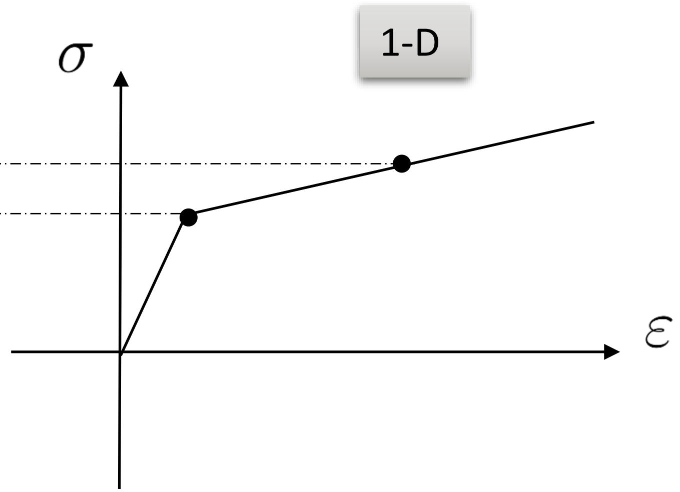
To answer these two questions, we need to introduce two hardening modes:

- Isotropic hardening
- Kinematic hardening

Metal Plasticity: Isotropic Hardening

For *isotropic hardening*, the yield surface expands uniformly in the radial direction.

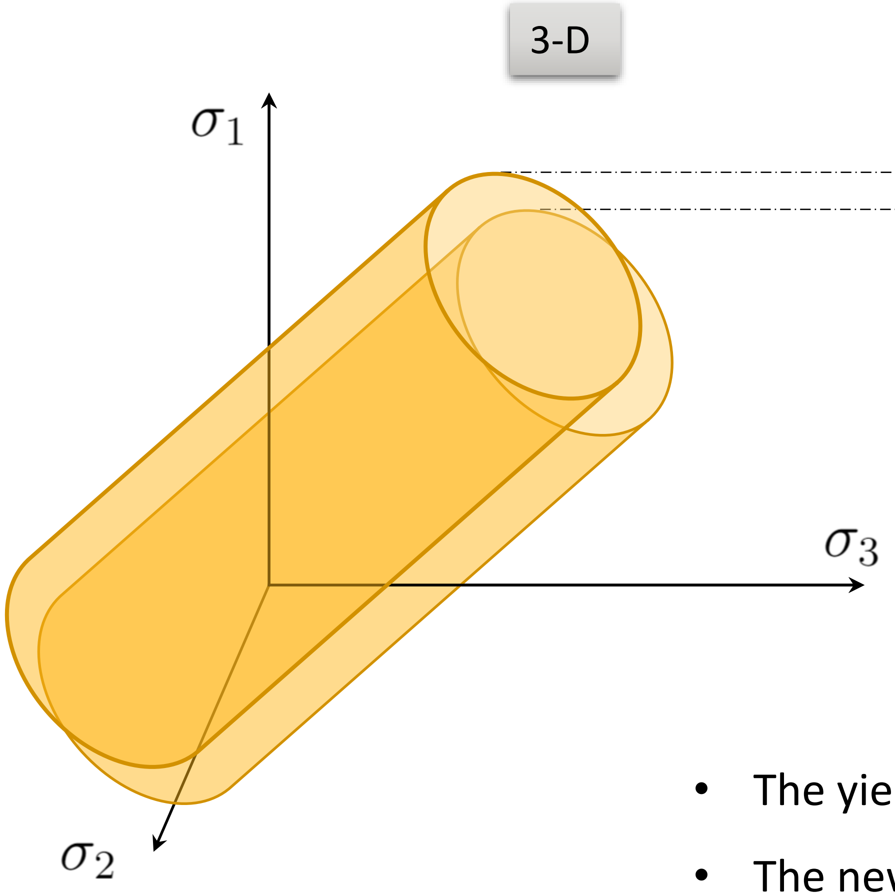


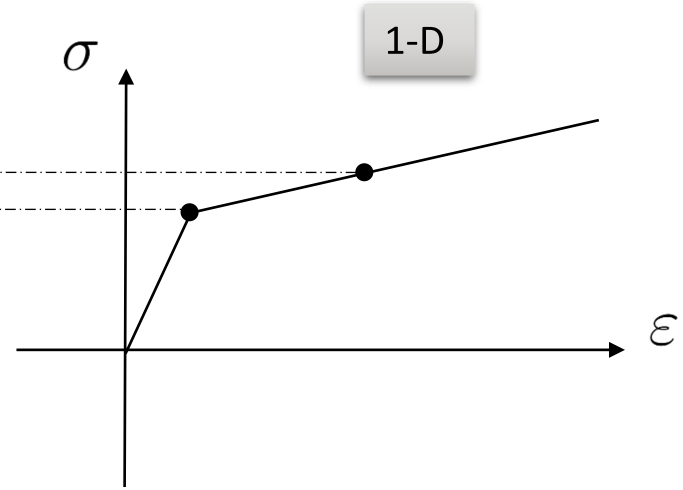


- One yield surface corresponds to one von Mises stress value in a 1D plot.
- A larger von Mises stress corresponds to a yield surface with a larger radius.

Metal Plasticity: Kinematic Hardening

For *kinematic hardening*, the yield surface is transformed to a new location.



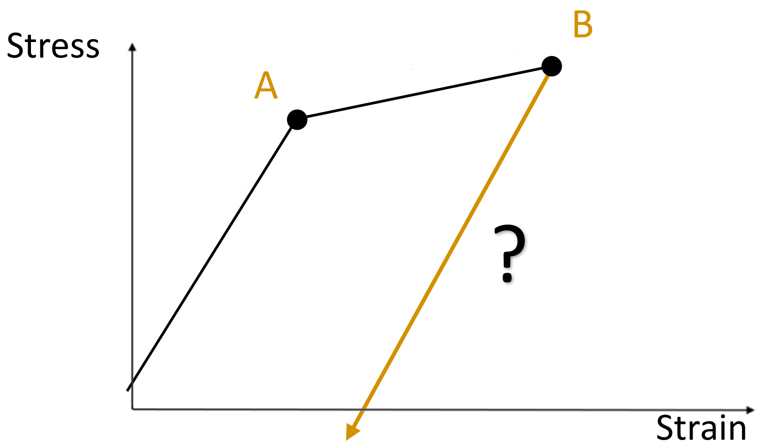


- The yield surface remains the same shape and size. It is a rigid transformation.
- The new surface corresponds to one von Mises stress on the 1D plot.

Metal Plasticity: Hardening for Cyclic Loading

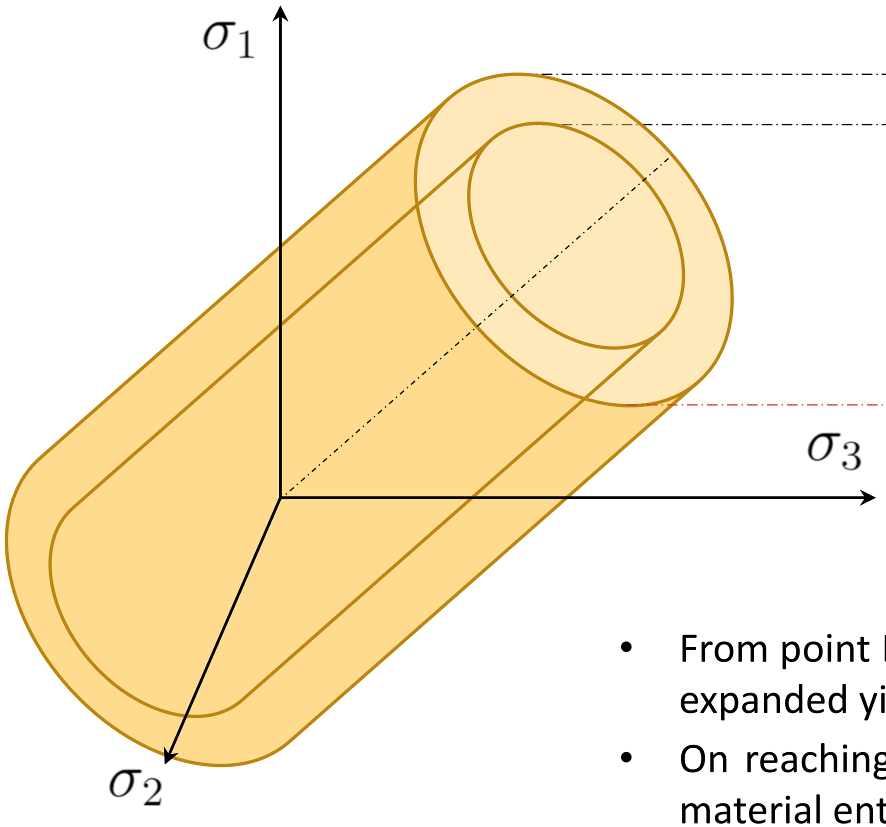
After unloading, the material will return inside the yield surface and become elastic again. If we continue the unloading after reaching zero load, it becomes loading in the opposite direction. Such a load pattern is called cyclic loading.

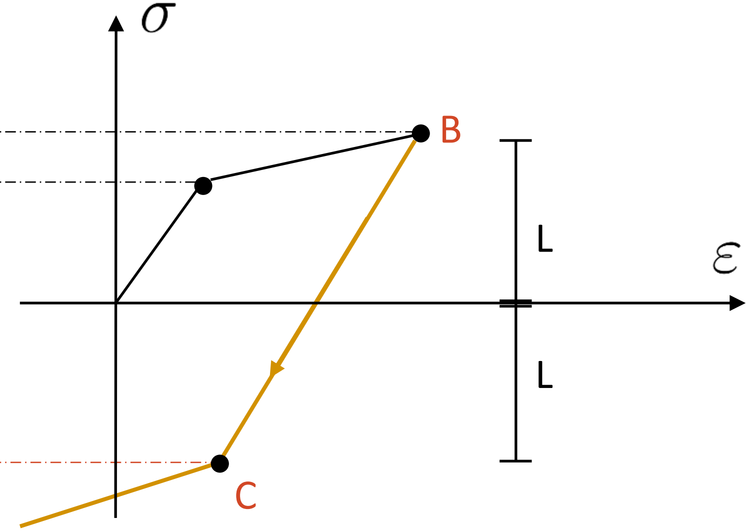
- For monotonic loading (point A to B), although the 3D yield surface behaves differently, the hardening results are the same for the two kinds of hardening modes.
- However, for cyclic loading, the different behavior of the yield surface will lead to different material behaviors.



Metal Plasticity: Isotropic Hardening for Cyclic Loading

For *isotropic hardening in cyclic loading*, the yield points are symmetric to the 0 stress axis inside one cycle.

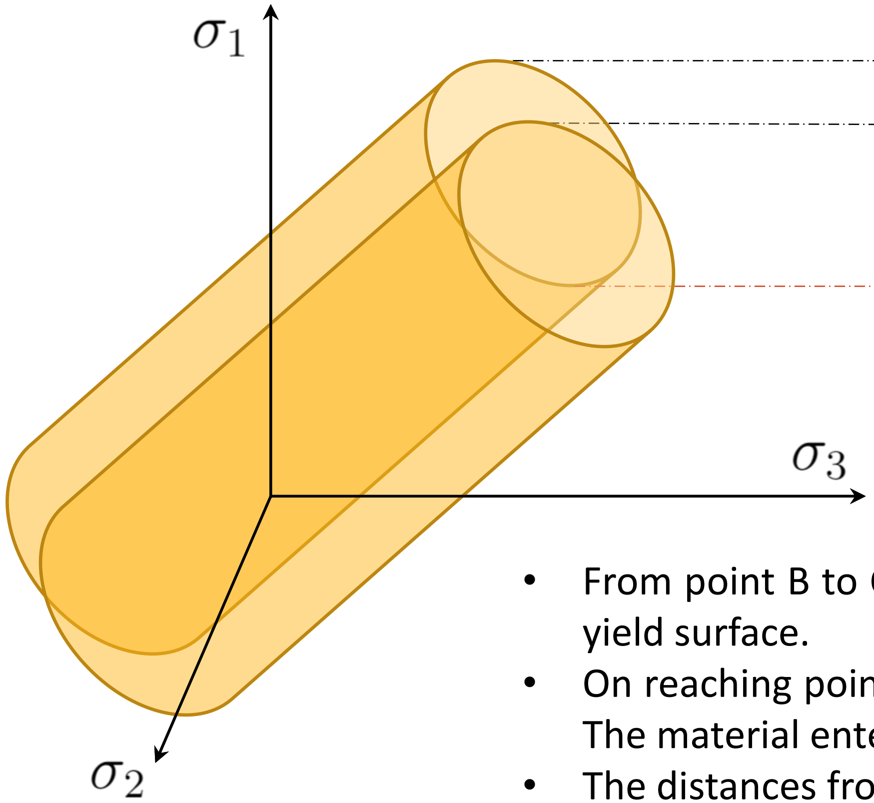


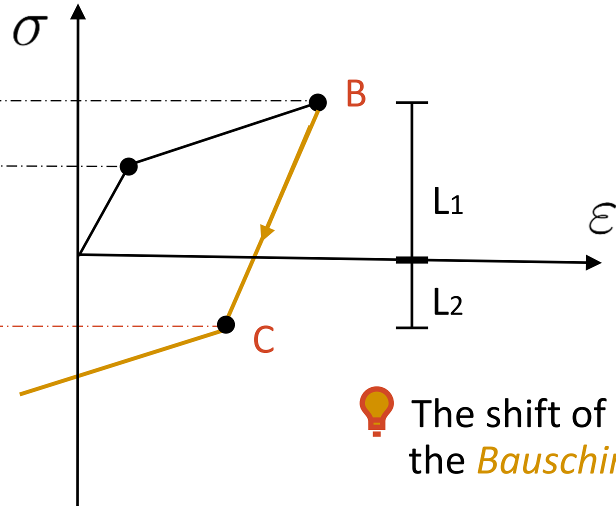


- From point B to C, the material returns to an elastic state. The material status remains inside the expanded yield surface.
- On reaching point C, the material status reaches the other side of the cylindrical surface. The material enters plasticity again.
- The distances from point B to 0 stress axis and from point C to 0 stress axis are the same.

Metal Plasticity: Kinematic Hardening for Cyclic Loading

For *kinematic hardening in cyclic loading*, the yield points are not symmetric to the 0 stress axis.





The shift of yield point is called the *Bauschinger effect*

- From point B to C, the material returns to elastic. The material status remains inside the shifted yield surface.
- On reaching point C, the material status reaches the other side of the shifted cylindrical surface. The material enters plasticity again.
- The distances from point B to 0 stress axis and from point C to 0 stress axis are different.

Metal Plasticity: Isotropic and Kinematic Hardening

Choice between isotropic and kinematic hardening for simulation of a material.

- The Bauschinger effect is observed for most metal materials in cyclic loading. It is a material's property that the compressive yield stress is reduced after a tensile loading.
- When load is monotonic, isotropic and kinematic hardening behave the same.
- When there is cyclic loading, isotropic hardening cannot simulate the Bauschinger effect. Therefore, when the material is expected to be under cyclic loading, kinematic hardening should be used to simulate the material.
- The behavior of isotropic and kinematic hardening is not specific for von Mises yield criteria. Such behavior is general for all yield criteria.

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