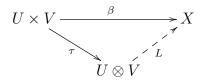
Read: Lax, Chapter 5, pages 55–56, and Appendix 4, pages 313–316.

1. Let U, V, and X be vector spaces over a field K. Define a map

$$\tau: U \times V \longrightarrow U \otimes V, \qquad \tau(u, v) = u \otimes v.$$

- (a) Prove that τ is bilinear.
- (b) Prove that for any linear map $L: U \otimes V \to X$, the mapping $\beta := L \circ \tau$ is bilinear.
- (c) Prove the universal property of tensor products: for any bilinear map $\beta: U \times V \to X$, there is a unique linear mapping $L: U \otimes V \to X$ such that $\beta = L \circ \tau$:



- 2. If $\{u_1, \ldots, u_n\}$ and $\{v_1, \ldots, v_m\}$ are bases for U and V, then the pure tensors $\{u_i \otimes v_j \mid 1 \leq i \leq n, 1 \leq j \leq m\}$ clearly span $U \otimes V$. Show that these are linearly independent, and conclude that $\dim(U \otimes V) = (\dim U)(\dim V)$. [Hint: Apply the universal property to the canonical basis $\{f_{ij}\}$ of bilinear functions $U \times V \to K$.]
- 3. Use the universal property of the tensor product to prove the following results:
 - (a) $U \otimes V \cong V \otimes U$ (hint: let $X = V \otimes U$);
 - (b) $(U \otimes V) \otimes W \cong U \otimes (V \otimes W);$
 - (c) $(U \times V) \otimes W \cong (U \otimes W) \times (V \otimes W)$.
- 4. Let W be a vector space with basis $\{w_{ij} \mid 1 \leq i \leq n, 1 \leq j \leq m\}$. Define the linear map

$$\alpha \colon W \longrightarrow U \otimes V, \qquad \alpha \colon w_{ij} \longmapsto u_i \otimes v_j.$$

To show this is an isomorphism, we would like to define the (inverse) map $\beta: U \otimes V \to W$. But to do so, we would need a basis for $U \otimes V$. So instead, define a map

$$\tilde{\beta} \colon F_{U \times V} \longrightarrow W, \qquad \tilde{\beta} \colon e_{\Sigma a_i u_i, \Sigma b_j v_j} \longmapsto \sum_{i,j} a_i b_j w_{ij}.$$

where $F_{U \times V}$ is the free vector space with basis $U \times V$:

$$F_{U \times V} = \left\{ \sum c_{uv} e_{u,v} \quad | \quad u \in U, \ v \in V \right\}.$$

- (a) Show that $N_q \subseteq N_{\tilde{\beta}}$, where $q: F_{U \times V} \to U \otimes V$ is the canonical quotient, and apply the universal property of quotient maps (see HW 3) to get a map $\beta: U \otimes V \to W$.
- (b) Show that α and β are inverses by verifying that $\alpha \circ \beta = \mathrm{Id}_{U \otimes V}$ and $\beta \circ \alpha = \mathrm{Id}_W$.