We typically think of building a $\Delta$-complex $X$ inductively. The 0-simplices (i.e., points), or vertices, form the 0-skeleton $X^{(0)}$. $n$-simplices $\sigma^n = [v_0, \ldots, v_n]$ attach to the $(n - 1)$-skeleton to form the $n$-skeleton $X^{(n)}$; the restriction of the attaching map to each face of $\sigma^n$ is, by definition, an $(n - 1)$-simplex in $X$. The attaching map is (by induction) really determined by a map $\{v_0, \ldots, v_n\} \rightarrow X^{(0)}$, since this determines the attaching maps for the 1-simplices in the boundary of the $n$-simplex, which gives 1-simplices in $X$, which then give the attaching maps for the 2-simplices in the boundary, etc. Note that the reverse is not true; the vertices of two different $n$-simplices in $X$ can be the same. For example, think of the 2-sphere as a pair of 2-simplices whose boundaries are glued by the identity. $\Delta$-complexes generalize simplicial complexes where the simplices are required to attach by homeomorphisms to the skeleton, and the intersection of two simplices are a (single) sub-simplex of each. This has the advantage over $\Delta$-complexes that an $n$-simplex is determined uniquely by the set of vertices in $X^{(0)}$ that it attaches to. This means that, in principle, a simplicial complex (and everything associated with it, e.g., its homology groups!) can be treated purely combinatorially; the complex is “really” a certain collection of subsets of the vertices (since these determine the simplices), with the property that any subset $B$ of a subset $A$ that has been declared to be a simplex is also a simplex. But they have the disadvantage that it typically takes far more simplices to build a simplicial structure on a space $X$ that it does to build a $\Delta$-structure. This makes the computations we are about to do take far longer.

The final detail that we need before defining (simplicial) homology groups is the notion of an orientation on a simplex of $X$. Each simplex $\sigma^n$ is determined by a map $f : \{v_0, \ldots, v_n\} \rightarrow X^{(0)}$; an orientation on $\sigma^n$ is an (equivalence class of) the ordered $(n + 1)$-tuple $(f(v_0), \ldots, f(v_n)) = (V_0, \ldots, V_n)$. Another ordering of the same vertices represents the same orientation if there is an even permutation taking the entries of the first $(n + 1)$-tuple to the second. This should be thought of as a generalization of the right-hand rule for $\mathbb{R}^3$, interpreted as orienting the vertices of a 3-simplex. Note that there are precisely two orientations on a simplex.

Now to define homology! We start by defining $n$-chains; these are (finite) formal linear combinations of the (oriented!) $n$-simplices of $X$, where $-\sigma$ is interpreted as $\sigma$ with the opposite (i.e., other) orientation. Adding formal linear combinations formally, we get the $n$-th chain group $C_n(X) = \{\sum n_\alpha \sigma_\alpha : \sigma_\alpha$ an oriented $n$-simplex in $X\}$. We next define a boundary operator $\partial : C_n(X) \rightarrow C_{n-1}(X)$, whose image will be the $(n - 1)$-chains that are the “boundaries” of $n$-chains. The idea is that the boundary of a 2-simplex, for example, should be a “sum” of its three faces (since they do make up the boundary of the simplex), but we need to take into account their orientations, in order to be getting the correct sum. Thinking of the orientation on a 1-simplex $[v, w]$ as an arrow pointing from $v$ to $w$, we are lead to believe that the boundary of a 2-simplex $[u, v, w]$ should be $[u, v] + [v, w] + [w, u]$. Similarly, the boundary of $[u, v]$, on reflection, should be $[v] - [u]$, to distinguish the head of the arrow (the + side) from the tail (the - side). On the basis of these examples, trying to find a consistent formula, one might eventually be led to the following formulation. We define the boundary on the basis elements $\sigma_\alpha = \sigma$ of $C_n(X)$ as $\partial \sigma = \sum (-1)^i \sigma|_{[v_0, \ldots, \hat{v_i}, \ldots, v_n]}$, where $\sigma : [v_0, \ldots, v_n] \rightarrow X$ is the characteristic map of $\sigma_\alpha$. $\partial \sigma$ is therefore an alternating sum of the faces of $\sigma$. We then extend the definition by linearity to all of $C_n(X)$. When a notation indicating dimension is needed, we write $\partial = \partial_\alpha$. We define $\partial_0 = 0$.

This definition, it turns out, is cooked up to make the maximal “boundaries have no boundary” true; that is, $\delta_{n} \circ \delta_{n} = 0$, the 0 map. This is because, for any simplex $\sigma = [v_0, \ldots, v_n]$,

$$\delta \circ \delta(\sigma) = \delta(\sum_{i=0}^{n} (-1)^i \sigma|_{[v_0, \ldots, \hat{v_i}, \ldots, v_n]})$$

$$= (\sum_{j<i} (-1)^j (-1)^i \sigma|_{[v_0, \ldots, \hat{v_j}, \ldots, \hat{v_i}, \ldots, v_n]}) + (\sum_{j>i} (-1)^{j-1} (-1)^i \sigma|_{[v_0, \ldots, \hat{v_i}, \ldots, \hat{v_j}, \ldots, v_n]})$$

The distinction between the two pieces is that in the second part, $v_j$ is actually the $(j - 1)$-st vertex of
the face. Switching the roles of $i$ and $j$ in the second sum, we find that the two are negatives of one another, so they sum to 0, as desired.

And this little calculation is all that it takes to define homology groups! What this tells us is that $\text{im}(\delta_{n+1}) \subseteq \ker(\delta_n)$ for every $n$. $\ker(\delta_n) = Z_n(X)$ are called the $n$-cycles of $X$; they are the $n$-chains with 0 (i.e., empty) boundary. They form a (free) abelian subgroup of $C_n(X)$. $\text{im}(\delta_{n+1}) = B_n(X)$ are the $n$-boundaries of $X$; they are, of course, the boundaries of $(n+1)$-chains in $X$. The $n$-th homology group of $X$, $H_n(X)$ is the quotient $Z_n(X)/B_n(X)$; it is an abelian group.

A key observation is that the boundary maps $\delta_n$ are linear, that is, they are homomorphisms between the free abelian groups $\delta_n : C_n(X) \rightarrow C_{n-1}(X)$. Consequently, they can be expressed as (integer-valued) matrices $\Delta_n$. Row reducing $\Delta_n$ (over the integers!) allows us to find a basis $v_1, \ldots, v_k$ for $Z_n(X)$ (clearing denominators to get vectors over $\mathbb{Z}$). Then since $\Delta_n \Delta_{n+1} = 0$, the columns of $\Delta_{n+1}$ are in the kernel of $\Delta_n$, so can be expressed as linear combinations of the $v_i$. These combinations can be determined by row reducing the augmented matrix $(v_1 \ldots v_k | \Delta_{n+1})$. This will row reduce to 

$$
\begin{pmatrix}
I & C \\
0 & 0
\end{pmatrix},
$$

and $C$ basically describes the boundaries $B_n(X)$ in terms of the basis $v_1, \ldots, v_k$. The homology group $H_n(X)$ is then the cokernel of $C$, i.e., $\mathbb{Z}^k / \text{im} C$. Note that $C$ will have integer entries, since we know that the columns of $\Delta_{n+1}$ can be expressed as integer linear combinations of the $v_i$, and, being a basis, there is only one such expression.