principal obtectomeran groups originated around the late Palaeocene epoch (~60 million years ago)[10], by which time microchiropteran bats had evolved echolocation[11]. We conclude that predation by bats imposed a great selection pressure on the evolution of ears in Lepidoptera.

Butterflies are the largest and most diverse group of diurnal Lepidoptera, and the selection pressures generally proposed for their diurnality include various physiological and ecological factors, but not selection pressure by bats. Given the significant impact of bats on other obtectomeran taxa, we suggest that diurnality in non-hedylid butterflies was also an anti-bat strategy, promoted by selection for individuals that avoided bats by appearing during the day. The butterfly, in effect, was therefore 'invented' by the bat.

Is the earless condition of other (non-hedylid) butterflies primitive or secondarily derived? Consider the Vogel's organ, a forewing structure of unknown function that is distributed sporadically with varying degrees of development among certain Papilionoidea[12,13]. Our comparative anatomical studies show that the hedylid ear and Vogel's organ are homologous structures. Given the current placement of the Hedyloidea as a sister-group to the Papilionoidea and Hesperoidea, it is possible that Vogel's organ is a degenerate 'bat detector'. Our discovery may help to bring to light the evolutionary origin of this group of butterflies.

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Alloys

Atomic structure of the quasicrystal $Al_{72}Ni_{20}Co_8$

Steinhardt *et al.*[1] reported experimental evidence in support of the coverage model[2–4] by presenting a structure for the high-perfection decagonal quasicrystal $Al_{72}Ni_{20}Co_8$. The coverage model describes the decagonal quasicrystals by a single type of tile, a decagon, the basic 2-nm cluster of which is allowed to overlap so as to cover the surface. Although their *Z*-contrast image (also referred to as a high-angle annular dark-field image) supports the coverage model, we find that the atomic structure they propose for the decagon has significant shortcomings which are inconsistent with our *Z*-contrast images.

The correct atomic structure of the decagon is critical to understanding how and why quasicrystals form. We have investigated the same high-perfection decagonal quasicrystal $Al_{72}Ni_{20}Co_8$ (provided by A. P. Tsai) by *Z*-contrast imaging, but at a higher spatial resolution (~0.13 nm) than Steinhardt *et al.*[1].

The main feature in the proposed structure of the decagon[1] is the extensive broken decagonal symmetry for the entire cluster (Fig. 1a) which enables the decagons to have identical subtiles, as suggested by the Gummelt coverage model, ensuring that the overlap rules required by this model are satisfied.

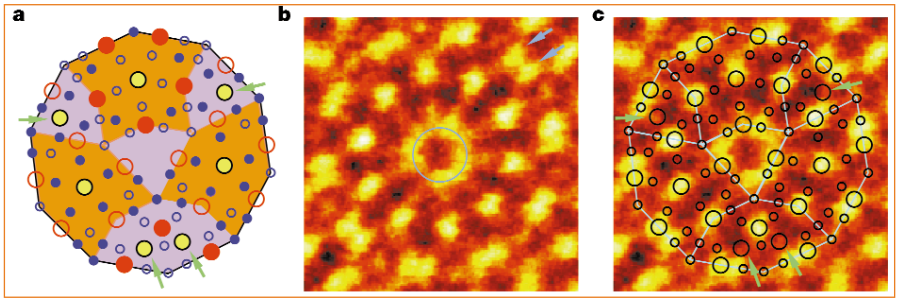

Figure 1 Comparison of the proposed "best-fit candidate model"[1] for the 2-nm cluster of the high-perfection decagonal quasicrystal $Al_{72}Ni_{20}Co_8$ with our higher resolution *Z*-contrast image. **a,** The proposed model contains broken decagonal symmetry for the entire cluster: see, for example, the four yellow columns indicated by green arrows. **b,** *Z*-contrast image of a 2-nm cluster of the same high-perfection decagonal quasicrystal $Al_{72}Ni_{20}Co_8$ along the ten-fold axis. The bright yellow features show the locations of highest intensity corresponding to high transition-metal (TM) occupancy. Al columns have lower intensity and are seen as red features: see, for example, the ten red spokes around the central ring. These spokes connect the central ring to the ring of ten TM columns (yellow) and show the basic ten-fold symmetry of the cluster. **c,** The model cluster of Steinhardt *et al.* superimposed on our *Z*-contrast image shows that their four proposed TM columns indicated by green arrows are not present.

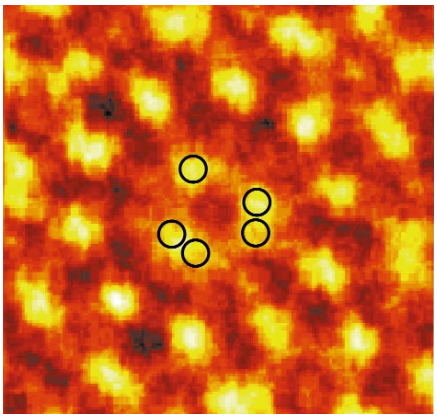

Figure 2 Cluster showing broken decagonal symmetry within the central ring, but there are still ten columns present, five of which have higher intensities (yellow), indicating high TM occupancy, whereas the other five show high Al occupancy (red). One of the five TM columns is a single column; the others form closely spaced column pairs, very similar to those in the outer 2-nm ring.

However, it is hard to see how a structure with such extensive broken symmetry can be energetically stable. Figure 1b shows a typical *Z*-contrast image of clusters that do not have strong broken symmetry. In a *Z*-contrast image, the intensity is directly correlated with the mean-square atomic number (Z), so that transition metal (TM) columns are seen with much higher intensity than Al columns.

The superimposition in Fig. 1c shows that the structure of the decagon proposed by Steinhardt *et al.* does not match our *Z*-contrast image in significant ways: the four proposed TM columns causing the broken symmetry are definitely absent from our image. In addition, our image reveals the presence of ten closely spaced TM column pairs in the outermost ring of the cluster, as indicated by double blue arrows in Fig. 1b. These are only single TM columns in the model of Steinhardt *et al.*

Turning to the central ring, our image clearly shows its underlying ten-fold symmetry. It is seen as a ring, with an intensity varying between that of an Al column (red) and a TM column (yellow). This is inconsistent with Steinhardt *et al.*'s triangular arrangement. This intensity pattern shows that there are ten closely spaced atomic columns around the central ring with a composition intermediate between that of an Al column and a TM column. However, there are many clusters with broken symmetry in the central ring.

Figure 2 is a typical *Z*-contrast image of such a cluster where the intensity in the central ring shows broken decagonal symmetry. The intensity distribution shows that

there are still ten closely spaced columns at the central ring, but now only five have higher intensities indicating high TM occupancy, whereas the intensity of the remainder is closer to that of an Al column. This indicates that the broken symmetry at the central ring is due to chemical ordering, and that there are ten sites, but with different TM and Al occupancies. This is also inconsistent with the triangular arrangement proposed by Steinhardt *et al.*

There are significant differences between the structure model proposed by Steinhardt *et al.* and our atomic-resolution *Z*-contrast image. Although these do not invalidate the coverage picture, they do prevent our understanding the formation of quasicrystals.

We believe that the closely spaced column pairs in the central and outermost rings that were not predicted by the structure model of Steinhardt *et al.* are the key to understanding the formation of decagonal quasicrystals. They not only show that the structures of the decagonal quasicrystals and their crystalline approximants are more similar than Steinhardt *et al.* suppose, they also highlight the critical differences. On this basis, we have proposed a growth mechanism[5] that explains why these clusters prefer to overlap and follow the Gummelt coverage picture. Our growth model predicts that the overall structure will show ideal quasicrystal tiling, in the Gummelt coverage picture, when all clusters have strong chemical ordering in the central rings. If the clusters have no chemical ordering, the model predicts a random tiling. For real quasicrystals, their structure might be a mixture of both cases.

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Steinhardt et al. *reply* — The purpose of our Letter[1] was to present experimental support for the quasi-unit cell picture of quasicrystals. This model proposes that the atomic structure can be reduced to a single repeating cluster satisfying certain 'overlap rules' (sharing of atoms by neighbouring clusters). We proposed that the quasicrystalline phase of AlNiCo can be decomposed into a repeating decagonal atom cluster (20 Å in radius). Yan and Pennycook do not refute the quasi-unit cell concept — they also propose a repeating cluster obeying the same

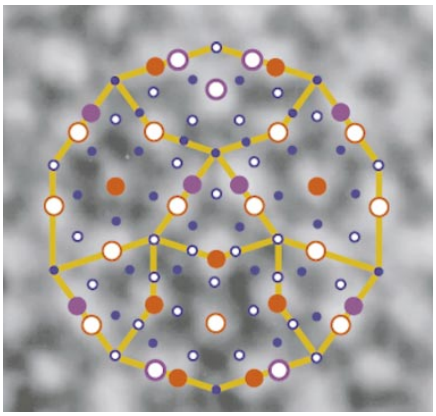

Figure 1 Improved decoration of the quasi-unit cell for AlNiCo compared to lattice image. Problematic TM sites in our earlier model[1] have been removed. The figure includes atoms added by overlap of neighbour clusters; these lead to the formation of neighbour TM column pairs, as seen near the centre. Large circles represent Ni (red) or Co (purple) and small circles represent Al. Solid circles represent $c=0$ and open circles represent $c=1/2$ along the periodic c-axis.

overlap rules. However, they propose a different atomic decoration for the repeating cluster that is ten-fold symmetric, whereas our decoration explicitly breaks ten-fold symmetry. This is important because our symmetry breaking corresponds precisely to the symmetry breaking of the overlap rules, and hence provides key evidence for the quasi-unit cell picture.

Yan and Pennycook's decoration is motivated by their impressive high-angle annular dark-field (HAADF) imaging, obtained with higher resolution than we had available. As they show, the imaging disagrees with the sites of four columns of transition metal (TM) atoms in our proposal (shown by arrows in their Fig. 1). However, we find that the problem can be resolved by a modest rearrangement of the previous decoration, switching 8 out of 100 atoms and retaining the broken ten-fold symmetry. The improved model in Fig. 1 has all the same qualitative properties as the original in ref. 1, matches the new HAADF (including Yan and Pennycook's Fig 2.) and even more recent high-resolution transmission electron microscopy (HRTEM) imaging, and has a density and stoichiometry that fits measured values to better than 2 per cent.

As more data become available (for example, from X-ray diffraction), further small refinements to our current best-fit decoration may be required, but the ten-fold symmetry breaking should remain as an essential property. The broken symmetry is necessary to explain three established features of AlNiCo: the broken symmetry consistently observed in through-focus HRTEM imaging of the clusters[2]; the broken symmetry found within the central ring of most clusters in HAADF imaging, such as our Fig. 1 and Yan and Pennycook's Fig. 2 (ref. 2) (the very rare, more symmetric rings, as shown in their Fig. 1, can be explained as defects; ref. 2 and M. Widom, personal communication); and the apparent quasiperiodic correlation in the broken symmetry direction on moving from cluster to cluster in HAADF images (see Fig. 1 of ref. 1), as is found for a configuration of overlapping decagons.

None of the features can be explained by symmetric clusters, even if chemical disorder is introduced to randomly break the ten-fold symmetry. M. Widom and coworkers (personal communication) have completed a total-energy-based prediction of the structure of AlNiCo, making no prior assumption about the existence of repeating 20-Å clusters. Yet decagonal clusters with broken ten-fold symmetry emerge as the lowest-energy configuration with nearly identical assignments of Al and TM positions, as in our improved model.

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Biological rhythms

Circadian clocks limited by noise

Circadian rhythms, which provide internal daily periodicity, are used by a wide range of organisms to anticipate daily changes in the environment[1]. It seems that these organisms generate circadian periodicity by similar biochemical networks within a single cell[2]. A model based on the common features of these biochemical networks shows that a circadian network can oscillate reliably in the presence of stochastic biochemical noise and when cellular conditions are altered. We propose that the ability to resist such perturbations imposes strict constraints on the oscillation mechanisms underlying circadian periodicity *in vivo*.

There is evidence that clock networks share common features in a wide range of organisms, from cyanobacteria to mammals[2]. For instance, all networks seem to include an interaction between two types of component (Fig. 1a): positive elements (or activators, such as KaiA in *Synechococcus*, Wc1-2 in *Neurospora*, Clc and Cyc in