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same is true if one of these planes is  $L_{\infty}$ . Thus the Hopf 7-spheres on  $S^{15}$  are parallel to one another, as claimed. QED

The Riemannian metric on the base space  $S^8$  which makes the Hopf projection  $S^{15} \rightarrow S^8$  into a Riemannian submersion is that of a round 8-sphere of radius 1/2, which one sees directly just as in the previous cases.

# 7. Symmetries of the Hopf fibration $H: S^7 \hookrightarrow S^{15} \to S^8$

PROPOSITION 7.1. The group G of all symmetries of the Hopf fibration  $H: S^7 \hookrightarrow S^{15} \to S^8$  is isomorphic to Spin(9), the simply connected double cover of SO(9).

The action is as follows:

- 1) There is a  $g \in G$  inducing any preassigned orientation preserving isometry of the round base  $S^8$ , but no orientation reversing ones.
- 2) Given such a g, there is exactly one other symmetry,

 $-g = antipodal map \circ g$ ,

which induces the same action on  $S^8$ .

It is likely that Élie Cartan was aware of this result, since in [Ca 2, esp. pp. 424 and 466] he identified Spin(9) as the group of isometries fixing a point in the Cayley projective plane  $CaP^2$ . It is not hard to see that this is the same as the group of symmetries of our Hopf fibration. The symmetry groups of the other Hopf fibrations can likewise be identified with the groups of isometries fixing a point in complex and quaternionic projective spaces, also known to Cartan.

We give the proof of Proposition 7.1 in a series of lemmas.

LEMMA 7.2. The only symmetries which take each fibre to itself are the identity and the antipodal map.

Suppose  $B: \mathbb{R}^{16} \to \mathbb{R}^{16}$  is such a symmetry. Since B maps

 $L_0 = \{(u, 0)\}, L_\infty = \{(0, v)\}$  and  $L_1 = \{(u, u)\}$ 

into themselves, we must have

$$B(u, v) = (A(u), A(v))$$

for some  $A \in O(8)$ . Since B maps  $L_m = \{(u, mu)\}$  into itself, we get

$$B(u, mu) = (A(u), A(mu)) = (A(u), mA(u)).$$
  

$$A(mu) = mA(u), \quad \text{all} \quad m, u \in Ca.$$

Thus

Now in this equation put u = 1 and keep m arbitrary:

$$A(m) = mA(1) = ma ,$$

where we define a = A(1). Insert this back into the previous equation, getting

$$(mu)a = m(ua)$$
, for all  $m, u \in Ca$ .

But then it follows from the nonassociativity of the Cayley numbers that the element a must be real. Since  $A \in O(8)$ ,  $a = \pm 1$ . Thus  $A(m) = \pm m$ , and hence  $B(u, v) = (\pm u, \pm v)$ , that is, B is either the identity or the antipodal map, as claimed. QED

If we compare Lemma 7.2 with the corresponding assertions about the earlier Hopf fibrations, we conclude that the current Hopf fibration is the least symmetric of all.

LEMMA 7.3. There is a symmetry of our Hopf fibration inducing any preassigned orientation preserving isometry of the base which keeps  $L_0$  fixed.

Such a symmetry must also take the orthogonal fibre  $L_{\infty} = \{(0, v)\}$  to itself, and hence must be of the form

 $(u, v) \mapsto (A(u), B(v))$ , where  $A, B \in O(8)$ .

Given such a symmetry, the Cayley line  $L_m = \{(u, mu)\}$  is taken to the set  $\{(A(u), B(mu))\}$ , which must itself be some Cayley line, say  $L_{m'}$ . Thus B(mu) = m' A(u). Note that as a function of u, the left hand side is conformal with conformal factor |m|, while the right hand side is conformal with factor |m'|. Hence |m| = |m'|. Since the correspondence  $m \mapsto m'$ is easily seen to be R-linear, it must be an isometry. Hence we can write m' = C(m), with  $C \in O(8)$ .

Summarizing so far, a symmetry of our Hopf fibration which takes the fibre  $L_0$  to itself must be of the form (A, B) with  $A, B \in O(8)$ , and there must exist a  $C \in O(8)$  such that

B(mu) = C(m) A(u), for all  $m, u \in Ca$ .

Vice versa, if such a C exists, then the map (A, B) is indeed a symmetry of the Hopf fibration.

Since it is C which describes the induced action on the base space  $S^8$ , we need to be able to preassign  $C \in SO(8)$ . The possibility of doing this is the content of the "Triality Principle", as follows.

LEMMA 7.4. (Triality Principle for SO(8), see [Ca 1, pp. 370 and 373] and [Fr]). Consider the triples A, B and C in SO(8) such that B(mu) = C(m) A(u), for all  $m, u \in Ca$ .

If any one of these three isometries is preassigned, then the other two exist and are unique up to changing sign for both of them.

We concentrate on preassigning C. Let G be the subset of SO(8) consisting of all transformations C for which there exist A and B in SO(8) satisfying the above equation for all  $m, u \in Ca$ . First note that G is actually a subgroup of SO(8). For suppose that C and C' are in G, and correspond as above to A, B and A', B' respectively. Then

$$BB'(mu) = B(C'(m) A'(u)) = CC'(m) AA'(u),$$

showing that  $CC' \in G$ . And similarly for inverses.

We want to show that G is all of SO(8). Let x be an imaginary Cayley number of unit length. We claim

(7.5) The right and left translations  $R_x$  and  $L_x$  are in G.

To show this, we use the first two Moufang identities.

To satisfy B(mu) = C(m) A(u) with  $C = R_x$ , choose  $A = -L_x R_x$  and  $B = R_x$ . We must show that

$$(mu)x = -(mx)(xux).$$

To do this, simply take the Moufang identity

$$z(xyx) = ((zx)y)x$$

and put x = x, y = u and z = mx, getting

$$(mx)(xux) = ((mxx)u)x = -(mu)x$$

since  $x^2 = -1$ . Thus  $R_x \in G$ .

To satisfy B(mu) = C(m) A(u) with  $C = L_x R_x$ , choose  $A = L_x$  and  $B = -L_x$ . We must show that

$$-x(mu) = (xmx)(xu)$$
.

To do this, take the Moufang identity

$$(xyx)z = x(y(xz))$$

and put x = x, y = m and z = xu, getting

$$f(xmx)(xu) = x(m(xxu)) = -x(mu),$$

since  $x^2 = -1$  as before. Thus  $L_x R_x \in G$ . Since we already know that G is a group and that it contains  $R_x$ , it must also contain  $L_x$ , establishing our claim.

Next we claim

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# (7.6) The transformations $R_x$ and $L_x$ , as x ranges over all imaginary unit Cayley numbers, generate SO(8).

Since the subgroup G contains these transformations, this will show that G is all of SO(8).

First note that any unit vector can be mapped to any other unit vector by a composition of such transformations. To see this, first suppose that u and v are orthogonal unit vectors:  $\langle u, v \rangle = 0$ . Then  $\langle 1, vu^{-1} \rangle = 0$ . Hence  $x = vu^{-1}$  is an imaginary unit Cayley number such that  $L_x(u)$  $= (vu^{-1})u = v$ . If u and v are unit vectors, but not necessarily orthogonal, just pick a unit vector w orthogonal to both. Find  $L_x$  and  $L_{x'}$  such that  $L_x(u) = w$  and  $L_{x'}(w) = v$ . Then  $L_{x'}L_x(u) = v$ , as desired.

So now it will be sufficient to show that any transformation in SO(8) keeping 1 fixed is a composition of right and left translations by imaginary unit Cayley numbers. One such transformation is  $-L_xR_x$  for any imaginary unit Cayley number x. Note that  $-L_xR_x(x) = x$ , so that this transformation also keeps x fixed. On the other hand, if y is an imaginary Cayley number orthogonal to x, then

$$-L_x R_x(y) = -xyx = xxy = -y,$$

since orthogonal imaginaries anti-commute by Fact 6. Thus  $-L_x R_x$  is the identity on the 2-plane spanned by 1 and x, and is minus the identity on the orthogonal 6-plane. Viewed just on the imaginary Cayley numbers, this transformation is reflection about the line through x.

But it is easy to see that the set of reflections through all lines in  $R^7$  generates SO(7). Hence the transformations  $R_x$  and  $L_x$ , as x ranges over all imaginary unit Cayley numbers, generate SO(8), as claimed.

Thus the subgroup G of transformations C in SO(8), for which one can find A and B in SO(8) satisfying B(mu) = C(m) A(u) for all Cayley

numbers m and u, must be all of SO(8). In a similar fashion, one can preassign either A or B and find the other two, completing the proof of existence for the Triality Principle.

To prove uniqueness up to sign change for the Triality Principle, suppose C is the identity. Thus B(mu) = m A(u) for all  $m, u \in Ca$ . Put m = 1 to learn that B(u) = A(u). So now A(mu) = m A(u). Put u = 1 to get A(m) = m A(1) = ma, where we define a = A(1). Then put this back in the previous equation to get (mu)a = m(ua). Since this holds for all  $m, u \in Ca$ , the element a must be real. Since A is orthogonal,  $a = \pm 1$ . Thus A = B $= \pm I$ , proving uniqueness up to sign change when C = I. Uniqueness up to sign change for all  $C \in SO(8)$  follows by composition. A similar argument gives uniqueness up to sign change when A or B is preassigned, completing the proof of the Triality Principle. QED

Preassigning C and using the Triality Principle to select A and B then completes the proof of Lemma 7.3: there is a symmetry of our Hopf fibration inducing any preassigned orientation preserving isometry of the base which keeps  $L_0$  fixed. QED

We next use Lemma 7.3 to sharpen itself.

LEMMA 7.7. There is a symmetry of our Hopf fibration inducing any preassigned orientation preserving isometry of the base. In particular, there is a symmetry taking any fibre to any other.

On the base space  $S^8$ , we take the north pole to be  $L_0$  and the south pole to be  $L_{\infty}$ . Then the equator will consist of all  $L_m$  for which |m| = 1. Now consider the circle consisting of the points  $L_m$  for real m. We plan to show that this circle is contained in the orbit of  $L_0$  under the symmetry group of H. Since this circle meets the equator in two points,  $L_1$  and  $L_{-1}$ , we can then use (7.3) to conclude that the orbit of  $L_0$ is all of  $S^8$ . Combining again with (7.3) will yield (7.7).

Consider the map  $A_{\phi}: Ca^2 \to Ca^2$  defined by

 $A_{\phi}(u, v) = (\cos \phi \ u - \sin \phi \ v, \sin \phi \ u + \cos \phi \ v).$ 

These maps, for  $0 \le \phi \le 2\pi$ , provide a circle group of isometries of  $Ca^2$ . We claim

(7.8) Each  $A_{\phi}$  is a symmetry of our Hopf fibration.



FIGURE 4

We must show that, given  $m \in Ca$ , there exists  $m' \in Ca$  such that  $A_{\phi}(L_m) = L_{m'}$ . Now

 $A_{\phi}(u, mu) = (\cos\phi \ u - \sin\phi \ mu, \sin\phi \ u + \cos\phi \ mu)$ =  $((\cos\phi - \sin\phi \ m) \ u, (\sin\phi + \cos\phi \ m) \ u).$ 

Let

and

Then

 $= (\cos\phi - \sin\phi m) u$ 

 $m' = (\sin\phi + \cos\phi m) (\cos\phi - \sin\phi m)^{-1}.$  $m'u' = [(\sin\phi + \cos\phi m) (\cos\phi - \sin\phi m)^{-1}] [(\cos\phi - \sin\phi m) u].$ 

The product on the right hand side may be reassociated because all the elements lie in the subalgebra of Ca spanned by the *two* elements *m* and *u*. As noted in section 5, such a subalgebra must be associative. But then clearly

$$m'u' = (\sin\phi + \cos\phi m) u$$
,

so that we have

u'

 $A_{\phi}(u, mu) = (u', m'u').$ 

Thus  $A_{\phi}(L_m) = L_{m'}$ , so each  $A_{\phi}$  is a symmetry of our Hopf fibration, as claimed.

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Since  $A_{\phi}(L_0) = L_{\tan\phi}$ , we see that the orbit of  $L_0$  under the various  $A_{\phi}$  is the circle  $(L_m: m \text{ real})$ . As indicated above, this is enough to complete the proof of (7.7). QED

LEMMA 7.9. No symmetry of our Hopf fibration can induce an orientation reversing isometry of the base.

Suppose there were such a symmetry. Using Lemma 7.7, we can assume it takes the fibre  $L_0 = \{(u, 0)\}$  to itself. Then it must be of the form  $(u, v) \mapsto (A(u), B(v))$  with  $A, B \in O(8)$ , and as we saw in (7.3) there must exist a  $C \in O(8)$  such that B(mu) = C(m) A(u) for all  $m, u \in Ca$ .

Composing our symmetry with an appropriate one guaranteed by Lemma 7.3 we can assume that  $C(m) = \bar{m}$ . Thus  $B(mu) = \bar{m} A(u)$ . Put m = 1 to conclude that A = B. Thus  $A(mu) = \bar{m} A(u)$ . Put u = 1 to conclude that  $A(m) = \bar{m} A(1) = \bar{m} a$ . Then put this back in the previous equation to get  $(\bar{mu})a = \bar{m}(\bar{u}a)$ . But  $\bar{mu} = \bar{u} \bar{m}$  by Fact 4 of section 5. Hence

$$(\bar{u} \ \bar{m})a = \bar{m}(\bar{u} \ a)$$
.

Now replace  $\bar{u}$  by u and  $\bar{m}$  by m to get

(um)a = m(ua) for all  $u, m \in Ca$ .

But this equation is impossible, which we see as follows.

Simply choose an automorphism of the Cayley numbers, see (5.4), which moves the element a to a unit quaternion. Apply such an automorphism to the above equation, and now consider that equation only for the quaternions:

(um)a = m(ua) for all  $u, m \in H$ .

But the quaternions are associative, so we remove the parentheses, then cancel the a and learn that

um = mu for all  $u, m \in H$ ,

which is of course false.

Proof of (7.1). Let G again denote the group of all symmetries of the Hopf fibration  $H: S^7 \hookrightarrow S^{15} \to S^8$ . Consider the homomorphism  $G \to O(9)$ , which takes each  $g \in G$  to its induced action on the base space  $S^8$ . By Lemma 7.9, the image lies in SO(9). By Lemma 7.7, the homomorphism is onto. By Lemma 7.2, it is two-to-one. Thus G is a double covering of SO(9). It remains to show that this covering is nontrivial.

QED

It will be sufficient to look only at the symmetries of H which take the fibre  $L_0 = \{(u, 0)\}$  to itself, and hence are of the form  $(u, v) \mapsto (A(u), B(v))$ . We already know that there must be a  $C \in SO(8)$  such that B(mu) = C(m) A(u)for all  $m, u \in Ca$ . To show that G is a nontrivial double covering of SO(9), we must find a loop of C's which lifts to a non-loop of (A, B)'s. This can be done by using the Moufang identities, just as in the proof of the Triality Principle. Recall from that proof that if x is an imaginary Cayley number of unit length, then  $A = L_x$ ,  $B = -L_x$  and  $C = L_x R_x$  "works", that is,  $-L_x(mu) = L_x R_x(m) L_x(u)$ . Now let x describe a semi-circular path in the i, j-plane from i to -i. At the beginning of the path, C(m) = imi, while at the end of the path C(m) = (-i)m(-i) = imi. Thus C describes a loop in SO(8). At the beginning of the path, (A(u), B(v))= (iu, -iv), while at the end (A(u), B(v)) = (-iu, iv). Hence (A, B) describes a non-loop in G. Thus G is the non-trivial double covering Spin(9) of SO(9).

Here is a further indication of the extent of symmetry of the Hopf fibration  $H: S^7 \hookrightarrow S^{15} \to S^8$ . Orient the fibres.

PROPOSITION 7.10. Let P and Q be any two fibres of H. Then a preassigned orientation preserving rigid motion of P onto Q can be extended to a symmetry of H. In particular, the symmetries act transitively on  $S^{15}$ .

By Lemma 7.7, the symmetries act transitively on fibres, so we may take  $P = Q = L_0$ . To preassign an orientation preserving rigid motion of  $L_0$  onto itself is to preassign the map  $A \in SO(8)$  in the Triality Principle, which then promises the desired symmetry of H. QED

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