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PERIODIC POINTS AND MEASURES FOR AXIOM A DIFFEOMORPHISMS

BY
RUFUS BOWEN

1. **Introduction.** We shall study the distribution of periodic points for a class of diffeomorphisms defined by Smale [16, §I.6].

We recall some of the definitions. Let $f: M \to M$ be a diffeomorphism of a compact manifold. A point $x \in M$ is *wandering* under f if it has a neighbourhood U such that $U \cap \bigcup_{m \neq 0} f^m(U) = \varnothing$; the set of other (i.e. nonwandering points) forms the *nonwandering set* $\Omega(f)$ which is closed and f-invariant. One sees that all periodic points of f are in $\Omega(f)$ and that any finite f-invariant measure on M has its support in $\Omega(f)$. A closed f-invariant subset Λ of M is *hyperbolic* under f if the tangent bundle of M restricted to Λ, $T_\Lambda(M)$, has a continuous splitting $T_\Lambda(M) = E^s + E^u$ which is invariant under Df and such that $Df: E^s \to E^s$ is contracting and $Df: E^u \to E^u$ is expanding (see [16, p. 758] for the meaning of these terms). *f satisfies Axiom* A if

(Aa) $\Omega(f)$ is hyperbolic and

(Ab) the periodic points of f are dense in $\Omega(f)$.

Smale's Spectral Decomposition Theorem [16, p. 777] states that for such an f we can write $\Omega(f) = \Omega_1 \cup \cdots \cup \Omega_r$ where the Ω_i are disjoint closed f-invariant sets and $f|\Omega_i$ is topologically transitive (the Ω_i are called *basic* sets). Our main result is that the periodic points of $f|\Omega_i$ have a definite limiting distribution as the period becomes large; this distribution is given by a measure μ_f on Ω_i. In the algebraic case μ_f turns out to be Haar measure.

We show that μ_f is ergodic, positive on open sets and zero on points (unless Ω_i is finite). In a subsequent paper [7] it is shown that $(f|\Omega_i, \mu_f)$ is a K-automorphism in the C-dense case (in fact that it is isomorphic to a Markov chain) and that μ_f is the unique invariant normalized Borel measure on Ω_i which maximizes entropy.

The Russian school has done much work on the measure theoretic aspects of Anosov diffeomorphisms (i.e. all of M hyperbolic under f); as a sampling we refer the reader to the papers [2], [14] and [15]. We also mention the papers [3], [9] and [11] where various measures are constructed for expanding maps; our methods are easily modified to give results along this direction also.

We now sketch our construction of μ_f. First we decompose $\Omega_i = X_1 \cup \cdots \cup X_m$ into disjoint closed pieces X_j such that $f(X_j) = X_{j+1}$ and $f^m | X_j: X_j \to X_j$ is *C-dense* for all $1 \leq j \leq m$. We do not define C-density here but it implies topological mixing

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and the existence of periodic points of all sufficiently large periods; for Markov chains this is the well-known decomposition into transitive pieces.

One then restricts attention to the C-dense case; i.e. assume $f\colon \Omega_i \to \Omega_i$ is C-dense. What we want is a measure μ_f such that (letting $N_n(E)$ be the number of fixed points of f^n lying in E)

$$N_n(E)/N_n(\Omega_i) \to \mu_f(E)$$

as $n \to \infty$ for many subsets E of Ω_i (we save precision for later). A priori we do not know that such a limit exists; using a diagonalization process we can choose sequences of integers $\{n_k\}$ and measures $\mu_{f,\{n_k\}}$ such that

$$N_{n_k}(E)/N_{n_k}(\Omega_i) \to \mu_{f,\{n_k\}}(E)$$

for many $E \subseteq \Omega_i$. We then show that all these measures $\mu_{f,\{n_k\}}$ are ergodic and equivalent; the Radon-Nikodym theorem tells us that they are all equal. When enough subsequences converge to a common limit, the sequence itself converges. Thus we get our desired $N_n(E)/N_n(\Omega_i) \to \mu_f(E)$.

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2. **Axiom A* and C-density.** Let $g\colon M \to M$ be a diffeomorphism satisfying Smale's Axiom A. Let $X = \Omega(g) \subseteq M$ and $f = g|X$. Define, for $x \in X = \Omega(g)$ and $\delta > 0$,

$$\begin{aligned} W^s_\delta(x) &= \{y \in X : d(f^n(x), f^n(y)) \leqq \delta \text{ for all } n \geqq 0\}. \\ W^u_\delta(x) &= \{y \in X : d(f^n(x), f^n(y)) \leqq \delta \text{ for all } n \leqq 0\}. \\ W^s(x) &= \{y \in X : d(f^n(x), f^n(y)) \to 0 \text{ as } n \to +\infty\}. \\ W^u(x) &= \{y \in X : d(f^n(x), f^n(y)) \to 0 \text{ as } n \to -\infty\}. \end{aligned}$$

Then (Smale [16, pp. 780–782] and Hirsch and Pugh [10]) the following are true:

A1. The periodic points of f are dense in X.

A2. For each $\delta > 0$ there is an $\varepsilon(\delta) > 0$ such that $W^s_\delta(x) \cap W^u_\delta(z) \neq \varnothing$ whenever $d(x, z) \leqq \varepsilon(\delta)$.

A3. There are $\delta^* > 0$, $0 < \lambda < 1$ and $c \geqq 1$ such that for all $n \geqq 0$,

$$d(f^n(x), f^n(y)) \leqq c\lambda^n d(x, y) \quad \text{if } y \in W^s_{\delta^*}(x)$$

and

$$d(f^{-n}(x), f^{-n}(y)) \leqq c\lambda^n d(x, y) \quad \text{if } y \in W^u_{\delta^*}(x).$$

The above statements are about f and do not refer to g or M. Any homeomorphism f of a compact metric space (X, d) we shall say *satisfies Axiom* A* provided that A1, A2, and A3 hold.

(2.1) *Standing hypothesis.* We shall assume throughout the remainder of the paper that $f\colon X \to X$ is a homeomorphism satisfying Axiom A*.

(2.2) *Easy facts.* (i) $f^n W^u(x) = W^u(f^n(x))$.

(ii) For $n \geqq 0, f^{-n} W^u_\delta(x) \subseteq W^u_\delta(f^{-n}(x))$.

(iii) If $y \in W_{\delta_1}(x)$, then $W_{\delta_2}(y) \subseteq W_{\delta_1+\delta_2}(x)$.

(iv) Let $f^m(x) = x$ and $\delta \leqq \delta^*$. Then $f^{m(k+1)} W^u_\delta(x) \supseteq f^{mk} W^u_\delta(x)$ and (by A3)

$$W^u(x) = \bigcup_{k=0}^{\infty} f^{mk} W^u_\delta(x).$$

The following fact is due to S. Smale and M. Shub:

(2.3) Lemma [6]. *δ^* is an expansive constant for f (i.e. if $x \neq y$, then $d(f^n(x), f^n(y)) > \delta^*$ for some $n \in Z$).*

(2.4) Lemma. *For any $\varepsilon > 0$ there is a $D(\varepsilon)$ so that $d(x, y) < \varepsilon$ whenever $d(f^n(x), f^n(y)) \leqq \delta^*$ for all $|n| \leqq D(\varepsilon)$.*

Proof. This is a property of expansive homeomorphisms [18].

(2.5) *Periodic point construction.* For any $\varepsilon > 0$ there are $\psi(\varepsilon) > 0$ and $R(\varepsilon)$ such that, if $m \geqq R(\varepsilon)$ and $d(f^m(y), y) \leqq \psi(\varepsilon)$, there is a point $z \in X$ with $f^m(z) = z$ and $d(f^k(z), f^k(y)) \leqq \varepsilon$ for all $0 \leqq k \leqq m$.

Proof. This is a translation of [6, Proposition 3.5] using [6, 3.4(h)].

(2.6) Definition. f (satisfying Axiom A*) is C-dense if $W^u(p)$ is dense in X for every periodic point $p \in X$.

We permute ideas of Smale [16, pp. 780–782] to obtain

(2.7) C-Density Decomposition Theorem. *$X = X_1 \cup \cdots \cup X_m$ where the X_i are disjoint closed sets, $f(X_i) = X_{g(i)}$ where g is a permutation of $(1, \ldots, m)$, and $f^r\colon X_i \to X_i$ is C-dense when $g^r(i) = i$.*

Proof. For p a periodic point let $X(p) = \mathrm{Cl}\,(W^u(p))$.

(a) *$X(p)$ is open.*

Proof. Let $a = \varepsilon(\delta^*)$. We show that

$$X(p) \supset B_a(X(p)) = \{y \in X : d(y, X(p)) < a\}.$$

Since $X(p)$ is closed, it suffices to show that periodic $q \in B_a(X(p))$ are in $X(p)$ because of A1. Let $x \in W^u(p)$ with $d(x, q) < a$ and set $M = \mathrm{ord}\, p \cdot \mathrm{ord}\, q$. By A2 choose $z \in W^u_{\delta^*}(x) \cap W^s_{\delta^*}(q)$. Then $z \in W^u(p)$ and

$$d(f^{kM}(z), q) = d(f^{kM}(z), f^{kM}(q)) \to 0 \quad \text{as } k \to +\infty.$$

Since $f^{kM} W^u(p) \subset W^u(p)$, we get $q \in \mathrm{Cl}\,(W^u(p)) = X(p)$. (Note: We use 2.1 without explicit mention.)

(b) *$X(p) = X(q)$ or $X(p) \cap X(q) = \varnothing$.*

Proof. Suppose $z \in X(p) \cap X(q)$. By (a) $X(p)$ is a neighborhood of z and so there is a $w \in W^u(q) \cap X(p)$. Let $M = \mathrm{ord}_f\, p \cdot \mathrm{ord}_f\, q$. Then as $k \to +\infty, f^{-kM}(w) \to q$. But $f^{-M} X(p) = X(p)$ since $f^{-M} W^u(p) = W^u(p)$. Thus $q \in \mathrm{Cl}\,(X(p)) = X(p)$. By (a) we have $X(p) \supset W^u_a(q)$. Since

$$W^u(q) \subset \bigcup_{k=0}^{\infty} f^{kM} W^u_a(q)$$

and $f^{kM}X(p)=X(p)$, we get $W^u(q)\subset X(p)$. Hence $X(q)\subset X(p)$. Symmetrically $X(p)\subset X(q)$.

Now by compactness, let $X=X(p_1)\cup\cdots\cup X(p_m)$ with $X(p_i)\neq X(p_j)$ for $i\neq j$. Set $X_i=X(p_i)$ and define g by $f(p_i)\in X_{g(i)}$. That f is a homeomorphism and (c) below show that g is a permutation.

(c) $f(X_i)=X_{g(i)}$.

Proof. As f is a homeomorphism, $fX(p_i)=X(f(p_i))$ follows from $fW^u(p_i)=W^u(f(p_i))$. Since $f(p_i)\in X(f(p_i))\cap X(p_{g(i)})$, $X(f(p_i))=X(p_{g(i)})$ by (b).

(d) *If $g^r(i)=i$, then f^r: $X_i\to X_i$ is C-dense.*

Proof. Suppose $p\in X_i$ is periodic. It is an easy exercise to check that $W^u_f(p)=W^u_{f^r}(p)$. Note that f^r: $X\to X$ satisfies Axiom A* whenever f: $X\to X$ does.

(2.8) LEMMA. *Let f: $X\to X$ be C-dense and $\alpha>0$. Then there is an N such that $f^mW^u_\alpha(x)\cap W^s_\alpha(y)\neq\varnothing$ whenever $x, y\in X$ and $m\geqq N$.*

Proof. Set $\delta=\min\{\delta^*, \frac{1}{2}\alpha, \frac{1}{4}\varepsilon(\frac{1}{2}\alpha)\}$ and choose $p_1, \ldots, p_r$ periodic such that every $x\in X$ is within $\frac{1}{2}\varepsilon(\frac{1}{2}\alpha)$ of some p_k. Let t_k be the period of p_k. By 2.2 and $\mathrm{Cl}(W^u(p_k))=X$, there is an m_k such that every $y\in X$ is within $\varepsilon(\delta)$ of $f^{mt_k}W^u_\delta(p_k)$ for $m\geqq m_k$. Let $N=(m_1t_1)\cdots(m_rt_r)$. Then $d(y, f^NW^u_\delta(p_k))\leqq\varepsilon(\delta)$ for all k and all $y\in X$.

Suppose x, $y\in X$. Then $d(x, p_j)<\frac{1}{2}\varepsilon(\frac{1}{2}\alpha)$ for some j and $d(y, z)\leqq\varepsilon(\delta)$ for some $z\in f^NW^u_\delta(p_j)$. Let $w\in W^u_\delta(z)\cap W^s_\delta(y)$. Then $f^{-N}(w)\in W^u_\delta(f^{-N}(z))\subset W^u_{2\delta}(p_j)$ and $d(f^{-N}(w), p_j)\leqq\frac{1}{2}\varepsilon(\frac{1}{2}\alpha)$; thus $d(f^{-N}(w), x)\leqq\varepsilon(\frac{1}{2}\alpha)$ and there is a $v\in W^s_{\alpha/2}(f^{-N}(w))\cap W^u_{\alpha/2}(x)$. Then $f^N(v)\in f^NW^u_\alpha(x)$ and $f^N(v)\in W^s_{\alpha/2}(w)\subset W^s_\alpha(y)$. Therefore $f^NW^u_\alpha(x)\cap W^s_\alpha(y)\neq\varnothing$, $\forall x, y\in X$. If $m\geqq N$, then

$$f^mW^u_\alpha(x)\cap W^s_\alpha(y)\supset f^NW^u_\alpha(f^{m-N}(x))\cap W^s_\alpha(y)\neq\varnothing.$$

(2.9) DEFINITIONS. Let $\mathrm{Per}_n(U)=\{x\in U : f^n(x)=x\}$, $N_n(U)=\mathrm{card}(\mathrm{Per}_n(U))$, and $N_n(f)=N_n(X)$.

A *G-time* is a finite collection $\tau=\{I_1, \ldots, I_m\}$ of disjoint (finite) intervals of integers. We let $\mathrm{Tim}(\tau)=\bigcup_{I\in\tau} I$, $T(\tau)=\mathrm{card}(\mathrm{Tim}(\tau))$, and $L(\tau)$ be the length of the shortest interval containing $\mathrm{Tim}(\tau)$. A map P: $\mathrm{Tim}(\tau)\to X$ is *(f, τ)-admissible* if $f^{t_2-t_1}$, $P(t_1)=P(t_2)$ whenever t_1, $t_2\in I\in\tau$ (i.e. $P(I)$ is part of an f-orbit). A *specification* is a pair $s=(\tau, P)$ with τ a G-time and P an (f, τ)-admissible map; set $L(s)=L(\tau)$ and $\mathrm{Tim}(s)=\mathrm{Tim}(\tau)$; we also write sometimes $\tau=\tau(s)$ or $P=P_s$. For $n\geqq0$ we say that τ is *n-delayed* if there is an interval of length at least n between every pair of invervals belonging to τ; s is n-delayed if $\tau(s)$ is. Notice that while $\mathrm{Tim}(\tau)$ does not determine τ, it does if τ is n-delayed with $n>0$.

Finally, for $\varepsilon>0$, let

$$U(s, \varepsilon)=\{x\in X : d(f^t(x), P_s(t)<\varepsilon \text{ for all } t\in\mathrm{Tim}(s)\}.$$

(2.10) THEOREM. *Suppose f: $X\to X$ is C-dense and $\varepsilon>0$. There is an $M(\varepsilon)$ such that $U(s, \varepsilon)\neq\varnothing$ whenever s is an $M(\varepsilon)$-delayed f-specification. In fact $M(\varepsilon)$ can be chosen so that* Per_d *$U(s, \varepsilon)\neq\varnothing$ for all $d\geqq M(\varepsilon)+L(s)$.*

Proof. We tend s to a new specification s' as follows. Let a_1 be the smallest integer in $\operatorname{Tim}(s)$. Set $\tau(s')=\tau(s)\cup\{\{a_1+d\}\}$ and define $P_{s'}$ by $P_{s'}(a_1+d)=P_s(a_1)$ and $P_{s'}|\operatorname{Tim}(s)=P_s$.

Set $\beta=\frac{1}{2}\min\{\psi(\frac{1}{2}\varepsilon), \varepsilon, \delta^*\}$ (ψ defined in 2.5) and $\alpha=\beta/3c$; let N be the integer given by 2.8 for this α. Choose $M=M(\varepsilon)\geqq\max\{N, R(\frac{1}{2}\varepsilon)\}$ (R defined in 2.5) large enough so that $\sum_{j=0}^{\infty}\lambda^{Mj}<2$. Assume $d\geqq M(\varepsilon)+L(s)$; then s' is M-delayed.

Let $I_1=[a_1, b_1]$, $I_2=[a_2, b_2]$, $\ldots$, $I_m=[a_m, b_m]=\{a_1+d\}$ be the members of $\tau(s')$ in their natural order. We set $z_1=x_1$ and define z_k (for $1\leqq k\leqq m$) recursively as follows. Suppose z_k has been chosen for some $1\leqq k<m$. As s^1 is M-delayed, $a_{k+1}-b_k>M\geqq N$ and so by 2.8 there exists a point

$$v\in f^{a_{k+1}-b_k}W^u_\alpha(f^{b_k}(z_k))\cap W^s_\alpha(P_{s^1}(a_{k+1})).$$

Set $z_{k+1}=f^{-a_{k+1}}(v)$; then $f^{b_k}(z_{k+1})\in W^u_\alpha(f^{b_k}(z_k))$ and $f^{a_{k+1}}(z_{k+1})\in W^s_\alpha(P_{s'}(a_{k+1}))$.

By induction on r we show that

$$f^{b_k}(z_{k+r})\in W^u_{c\alpha+c\alpha\lambda^M+\cdots+c\alpha\lambda^{M(r-1)}}(f^{b_k}(z_k)).$$

For $r=1$, this was seen above (since $c\geqq 1$). Assume the statement is true for some $r\geqq 1$. Since s^1 is M-delayed; $b_{k+r}-b_k\geqq rM$; because $f^{b_{k+r}}(z_{k+r+1})\in W^u_\alpha(f^{b_{k+r}}(z_{k+r}))$ we get

$$(*)\qquad f^{b_k}(z_{k+r+1})\in W^u_{c\alpha\lambda^{Mr}}(f^{b_k}(z_{k+r})).$$

(Here we use A3: If $x\in W^u_\alpha(y)$, then $d(f^{-n}(x), f^{-n}(y))\leqq c\alpha\lambda^n$ for $n\geqq 0$ and so $f^{-m}(x)\in W^u_{\alpha\lambda^m}(f^{-m}(y))$ for $m\geqq 0$.) Applying (*) and our inductive hypothesis, it follows that (see 2.2(ii))

$$f^{b_k}(z_{k+r+1})\in W^u_{c\alpha+\cdots+c\alpha\lambda^{Mr}}(f^{b_k}(z_k))$$

and so our induction is done.

Since $\sum_{j=0}^{\infty}\lambda^{Mj}<2$ and $\alpha=\beta/3c$ we have $f^{b_k}(z_m)\in W^u_{2\beta/3}(f^{b_k}(z_k))$ and $d(f^t(z_m), f^t(z_k))<2\beta/3$ for any $t\in I_k$ and any $k\in[1, m]$. Since $f^{a_k}(z_k)\in W^s_\alpha(P_{s^1}(a_k))$ (by the definition of the z_k's) we have

$$\beta/3 \geqq \alpha \geqq d(f^t(z_k), f^{t-a_k}(P_{s^1}(a_k))) = d(f^t(z_k), P_{s^1}(t))$$

for any $t\in I_k$. Combining inequalities,

$$d(f^t(z_m), P_{s^1}(t)) < \beta \quad \text{for all } t\in\operatorname{Tim}(s^1).$$

Thus $z_m\in U(s^1, \beta)$.

Now let $z^*=f^{a_1}(z_m)$. Then $z^*, f^d(z^*)\in B_\beta(P_s(a_1))$, and so $d(z^*, f^d(z^*))\leqq\psi(\frac{1}{2}\varepsilon)$. Now $d>M(\varepsilon)\geqq R(\frac{1}{2}\varepsilon)$ and by 2.5 there is a $z\in\operatorname{Per}_d(X)$ with

$$d(f^t(z), f^t(z^*)) \leqq \tfrac{1}{2}\varepsilon \quad \text{for all } 0\leqq t\leqq d.$$

Letting $z^1=f^{-a_1}(z)$ we get

$$d(f^t(z^1), f^t(z_m)) \leqq \tfrac{1}{2}\varepsilon \quad \text{for all } a_1 \leqq t \leqq a_1+d.$$

Applying the triangle inequality to this and $z_m \in U(s^1, \beta)$,

$$z^1 \in U(s^1, \beta+\tfrac{1}{2}\varepsilon) \subseteqq U(s^1, \varepsilon) \subseteqq U(s, \varepsilon);$$

also $z^1 \in \mathrm{Per}_d(X)$.

(2.11) REMARK. The above theorem is a statement about the freedom one has in specifying the approximate orbit of a periodic point. The remainder of this paper shall be derived from this freedom (together with expansiveness).

3. **Counting.** Throughout this section $f\colon X \to X$ is a C-dense map.

(3.1) DEFINITION. For $\varepsilon > 0$, $E \subset X$ is an *(n, ε)-separated* set if for any distinct $x, y \in E$ there is a t for which $0 \leqq t < n$ and $d(f^t(x), f^t(y)) > \varepsilon$. We let $N(n, \varepsilon)$ denote the maximum cardinality of an (n, ε)-separated set.

(3.2) LEMMA. (i) *If $\varepsilon \leqq \delta^*$, then $N(n, \varepsilon) \geqq N_n(f)$.*

(ii) *If $\varepsilon \leqq \alpha$, then $N(n, \alpha) \leqq N(n, \varepsilon)$; for any $\varepsilon > 0$ there is an m_ε such that $N(n, \varepsilon) \leqq N(n+m_\varepsilon, \delta^*)$ for all $n \geqq 0$.*

(iii) $N(\sum n_i, \varepsilon) \leqq \prod N(n_i, \tfrac{1}{2}\varepsilon)$.

Proof. (i) By 2.3 ε is an expansive constant; i.e. if $p \neq q$, then $d(f^t(p), f^t(q)) > \varepsilon$ for some t. If $p, q \in \mathrm{Per}_n(X)$, then t can be chosen so that $0 \leqq t < n$; i.e. $\mathrm{Per}_n(X)$ is (n, ε)-separated.

(ii) The first statement is obvious; if E is an (n, ε)-separated set, then $f^{-D(\varepsilon)}E$ is an $(n+2D(\varepsilon), \delta^*)$-separated set (use 2.4).

(iii) We prove the following stronger statement for later use: Suppose $E \subset X$ and n_i, m_i $(1 \leqq i \leqq s)$ are integers $(n_i > 0)$ such that, when $x, y \in E$ and $x \neq y$, there is a $t \in \bigcup_{i=1}^s [m_i, m_i+n_i)$ for which $d(f^t(x), f^t(y)) > \varepsilon$; then $\mathrm{card}\,(E) \leqq \prod_{i=1}^s N(n_i, \tfrac{1}{2}\varepsilon)$.

Proof. Choose $R_i \subset X$ so that $f^{m_i}R_i$ is a maximal $(m_{i_1}, \tfrac{1}{2}\varepsilon)$-separated set. Construct a map $g = \prod g_i\colon E \to \prod R_i$ by requiring that $d(f^t(x), f^t(g_i(x))) \leqq \tfrac{1}{2}\varepsilon$ for all $t \in [m_i, m_i+n_i)$. Such a $g_i(x)$ exists by the maximality of $f^{m_i}R_i$—otherwise $f^{m_i}(Ru\{x\})$ would be an $(n, \tfrac{1}{2}\varepsilon)$-separated set.

If $g(x) = g(y)$ the triangle inequality would give us $d(f^t(x), f^t(y)) \leqq \varepsilon$ for all $t \in \bigcup [m_i, m_i+n_i)$; thus g is injective and we are done.

Two specifications s and s^1 are *p-separated* if $d(P_s(t), P_{s^1}(t)) > p$ for some $t \in \mathrm{Tim}\,(s) \cap \mathrm{Tim}\,(s^1)$; a set of specifications is p-separated if every two members are. An *S-set A* is a set of specifications with the same G-time; let $\tau(A)$ denote this common G-time, $T(A) = T(\tau(A))$, $L(A) = L(\tau(A))$, and $U(A, \varepsilon) = \bigcup_{s \in A} U(s, \varepsilon)$.

3.3 LEMMA. (i) *If s and s^1 are p-separated, then $U(s, \tfrac{1}{2}p) \cap U(s^1, \tfrac{1}{2}p) = \varnothing$.*

(ii) *If A is a 2ε-separated S-set, $\tau(A)$ is $M(\varepsilon)$-delayed, and $d \geqq L(A) + M(\varepsilon)$, then $N_d(U(A, \varepsilon)) \geqq \mathrm{card}\,(A)$.*

Proof. (i) Trivial. (ii) Follows from (i) and 2.10.

Two specifications s and s^1 are disjoint if $\mathrm{Tim}\,(s) \cap \mathrm{Tim}\,(s^1) = \varnothing$. In this case we define a new specification $s \wedge s^1$ by $\tau(s \wedge s^1) = \tau(s) \cup \tau(s^1)$ and

$$\begin{aligned} P_{s\wedge s^1}(t) &= P_s(t) \quad \text{for } t \in \mathrm{Tim}\,(s), \\ &= P_{s^1}(t) \quad \text{for } t \in \mathrm{Tim}\,(s^1). \end{aligned}$$

Notice that $U(s \wedge s^1, \varepsilon) = U(s, \varepsilon) \cap U(s^1, \varepsilon)$. We call a G-time τ an *m-time* if card $\tau = m$; s is an m-specification if $\tau(s)$ is an m-time.

(3.4) LEMMA. *If τ is an n-delayed m-time and $N \geqq L(\tau)$, there is a τ^1 such that*
(a) $\mathrm{Tim}(\tau) \cap \mathrm{Tim}(\tau^1) = \varnothing$,
(b) *$\tau \cup \tau^1$ is n-delayed,*
(c) *$L(\tau \cup \tau^1) \leqq N$, and*
(d) *$T(\tau^1) \geqq N - 2mn - T(\tau)$.*

Proof. Let a_1 be the smallest integer in Tim (τ). Set

$$\mathrm{Tim}(\tau^1) = \{t \in [a_1, a_1 + N) : |t - r| > n \quad \text{for all } r \in \mathrm{Tim}(\tau)\}.$$

This determines a G-time τ which satisfies our condition.

(3.5) REMARK. τ^1 could be empty.

(3.6) LEMMA. *If τ is a time specification and $\varepsilon > 0$, there is an ε-separated S-set A with $\tau(A) = \tau$ and* card $(A) \geqq N(T(\tau), 2\varepsilon)$.

Proof. Let $\tau = \{I_1, \ldots, I_m\}$ and $\tau_k = \{I_k\}$ for $1 \leqq k \leqq m$. Let A_k be an ε-separated S-set with $\tau(A_k) = \tau_k$ and card $(A_k) = N(T(\tau_k), \varepsilon)$. Then

$$A = A_1 \wedge \cdots \wedge A_m = \{s_1 \wedge \cdots \wedge s_m : s_k \in A_k, 1 \leqq k \leqq m\}$$

is ε-separated with $\tau(A) = \tau_1 \wedge \cdots \wedge \tau_m = \tau$ and card $(A) = \prod N(T(\tau_k), \varepsilon) \geqq N(\sum T(\tau_k), 2\varepsilon) = N(T(\tau), 2\varepsilon)$ by 3.2(iii).

(3.7) THEOREM. *Suppose B is a 2ε-separated S-set with $\tau(B)$ an $M(\varepsilon)$-delayed m-time. Then*

$$N_d(U(B, \varepsilon)) \geqq \frac{K(m, \varepsilon) \operatorname{card}(B) N(d, 8\varepsilon)}{N(T(\tau(B)), 4\varepsilon)}$$

for all $d \geqq L(\tau(B)) + M(\varepsilon)$ where $K(m, \varepsilon) > 0$ depends only on m and $\varepsilon > 0$.

Proof. Let $N = d - M(\varepsilon) \geqq L(\tau(B))$. Let $\tau = \tau(B)$ and choose τ^1 as in Lemma 3.4. By Lemma 3.5 let A be a 2ε-separated S-set with $\tau(A) = \tau^1$ and card $(A) \geqq N(T(\tau^1), 4\varepsilon)$. Now $A \wedge B$ is a 2ε-separated S-set with $M(\varepsilon)$-delayed time $\tau \wedge \tau^1$; $d \geqq N + M(\varepsilon) \geqq L(\tau \wedge \tau^1) + M(\varepsilon)$. Hence, by 3.3(ii), we have

$$N_d(U(A \wedge B, \varepsilon)) \geqq \operatorname{card}(A \wedge B) = \operatorname{card}(A) \operatorname{card}(B).$$

Since $U(B, \varepsilon) \geqq U(A \wedge B, \varepsilon)$,

$$N_d(U(B, \varepsilon)) \geqq \operatorname{card}(A) \operatorname{card}(B).$$

Now $T(\tau^1) \geqq \max\{0, N - 2mM(\varepsilon) - T(\tau)\}$ (see Remark 3.5). Thus

$$\operatorname{card} A \geqq \max\{1, N(N - 2mM(\varepsilon) - T(\tau), 4\varepsilon)\} = W$$

(taking 1 in case $N - 2mM(\varepsilon) - T(\tau) \leqq 0$). Recalling that $N = d - M(\varepsilon)$ and 3.2(iii) we get

$$N(d, 8\varepsilon) \leqq W \cdot N((2m+1)M(\varepsilon), 4\varepsilon) N(T(\tau), 4\varepsilon)$$

(the inequality is good in the exceptional case we have been noting). Thus

$$N_d(U(B, \varepsilon)) \geqq \operatorname{card}(B) : W$$
$$\geqq \frac{K(m, \varepsilon) \operatorname{card}(B)\, N(d, \delta\varepsilon)}{N(T(\tau), 4\varepsilon)}$$

where $K(m, \varepsilon) = N((2m+1)M(\varepsilon), 4\varepsilon)^{-1}$.

(3.8) DEFINITION. For $U \subset X$ let

$$\varphi(U) = \liminf_{n\to\infty} \frac{N_n(U)}{N_n(f)} \quad \text{and} \quad \theta(U) = \limsup_{n\to\infty} \frac{N_n(U)}{N_n(f)}.$$

(3.9) COROLLARY. (i) *For any* $\alpha > 0$

$$\liminf_{d\to\infty} \frac{N_d(f)}{N(d, \alpha)} > 0.$$

(ii) $\varphi(V) > 0$ *when* $V \neq \varnothing$ *is open.*

(iii) *There is a* $K^* > 0$ *such that* $\varphi(U) \geqq K^*\theta(V)$ *whenever* U *and* V *are open in* X *and* $U \supset \bar{V}$.

(iv) *There are* m_0 *and* $S > 0$ *such that* $N_{m+n}(f) \geqq SN(m, \delta^*)N(n, \delta^*) \geqq SN_m(f)N_n(f)$ *provided that* $m \geqq m_0$.

(v) *There are* m_0 *and* $S > 0$ *such that, if* $m \geqq m_0$ *and* $U \subset X$ *satisfies* $\operatorname{diam} f^k(U) \leqq \delta^*$ *for all* $0 \leqq k < m$, *then* $\theta(U) \leqq 1/SN_m(f)$.

Proof. (i) and (ii). Let $x \in V$ and choose $\varepsilon > 0$ so small that $B_\varepsilon(x) \subset V$ and $8\varepsilon \leqq \min\{\alpha, \delta^*\}$. Let s be given by $\tau(s) = \{\{0\}\}$ and $P_s(0) = x$; $B = \{s\}$. Then $V \supset U(s, \varepsilon)$ and by the theorem

$$N_d(f) \geqq N_d(V) \geqq K(1, \varepsilon)\, N(d, 8\varepsilon)/N(1, 4\varepsilon)$$

for $d \geqq 1 + M(\varepsilon)$. As $N(d, 8\varepsilon) \geqq N(d, \alpha)$, (i) follows immediately. As $N(d, 8\varepsilon) \geqq N(d, \delta^*) \geqq N_d(f)$, so does (ii).

(iii) Choose $\varepsilon > 0$ so that $U \supset B_\varepsilon(V)$ and let $D(\varepsilon)$ be given as in 2.4. Consider $n > 2D(\varepsilon)$. For each $p \in \operatorname{Per}_n(V)$ form the 1-specification $s(p)$ with $\tau(s(p)) = \{[-D(\varepsilon), n - D(\varepsilon))\}$ and $P_{s(p)}(f) = f^t(p)$. $B_n = \{s(p) : p \in \operatorname{Per}_n(V)\}$ is δ^*-separated (see the proof of 3.2(iii)). By the definition of ε and $D(\varepsilon)$ we have $U(B_n, \delta^*) \subset U$.

Trivially, $U(B_n, \frac{1}{8}\delta^*) \subset U$; so by the theorem

$$N_d(U) \geqq K(1, \tfrac{1}{8}\delta^*) N_n(V) N(d, \delta^*)/N(n, \tfrac{1}{2}\delta^*)$$

for $d \geqq n + M(\frac{1}{8}\delta^*)$. By (i) above there is an n_0 and a K_1 such that $N(n, \frac{1}{2}\delta^*) \leqq K_1 N_n(f)$ when $n \geqq n_0$; also $N(d, \delta^*) \geqq N_d(f)$. Thus for $n \geqq n_0$ and $d \geqq n + M(\frac{1}{8}\delta^*)$ we have

$$N_d(U)/N_d(f) \geqq K^* N_n(V)/N_n(f)$$

where $K^* = K(1, \frac{1}{8}\delta^*)/K_1 > 0$. Then $\varphi(U) \geqq K^*\theta(V)$.

(iv) Set $m_0 = 2M(\frac{1}{4}\delta^*)$. Let A be a $\frac{1}{2}\delta^*$-separated S-set with $\tau(A) = \{[0, n)\}$ and card $A = N(n, \frac{1}{2}\delta^*)$; B a $\frac{1}{2}\delta^*$-separated S-set with $\tau(B) = \{[n + M(\frac{1}{4}\delta^*), n+m$

$-M(\frac{1}{4}\delta^*))\}$ and card $B=N(m-m_0, \frac{1}{4}\delta^*)$. Now $A \wedge B$ is $\frac{1}{2}\delta^*$-separated with $M(\frac{1}{4}\delta^*)$-delayed time.

By 3.3(ii) we have

$$N_{n+m}(f) \geqq \text{card}\,(A \wedge B) = N(n, \tfrac{1}{2}\delta^*)N(m-m_0, \tfrac{1}{2}\delta^*).$$

By Proposition 3.2(iii) we have

$$N(m, \delta^*) \leqq N(m-m_0, \tfrac{1}{2}\delta^*)N(m_0, \tfrac{1}{2}\delta^*).$$

Taking $S=N(m_0, \frac{1}{2}\delta^*)^{-1}$, $N_{n+m}(f) \geqq SN(n, \delta^*)N(m, \delta^*)$.

(v) Let m_0 and S be as above. Since $\text{Per}_{n+m}(U)$ is an $(n+m, \delta^*)$-separated set and diam $f^k(U) \leqq \delta^*$ for $0 \leqq k < m$, $f^m \,\text{Per}_{n+m}(U)$ is an (n, δ^*)-separated set; thus $N_{n+m}(U) \leqq N(n, \delta^*)$. By (iv) we have, since $m \geqq m_0$, $N_{n+m}(f) \geqq SN(n, \delta^*)N(m, \delta^*)$ and so

$$N_{n+m}(U)/N_{n+m}(f) \leqq 1/SN_m(f).$$

Letting $n \to \infty$, $\theta(U) \leqq 1/SN_m(f)$.

(3.10) Definition. For $A \subset X$ let $N(n, \varepsilon, A)$ be the largest cardinality of an (n, ε)-separated set contained in A.

(3.11) Proposition. *For each ε with $0<\varepsilon<\frac{1}{2}\delta^*$ there are constants $c_\varepsilon>0$ and $0<\tau_\varepsilon<1$ for which the following holds. If $A \subset X$, $0 \leqq k_1 < k_2 < \cdots < k_m$, are integers and $w_{k_1}, \ldots, w_{k_m} \in X$ satisfy $f^{k_r}(A) \cap B_\varepsilon(w_{k_r}) = \varnothing$ for $r=1, \ldots, m$, then $N(n, \varepsilon, A) \leqq c_\varepsilon \tau^m N(n, \varepsilon)$ for all $n > k_m$.*

Proof. Let $M=M(\frac{1}{2}\varepsilon)$ as in 2.10. Let $j_1<j_2<\cdots<j_q$ be a subsequence of $k_1<\cdots<k_m$ such that $j_{i+1}-j_i>2M$ and $q \geqq m/(2M+1)$. Let $n>k_m$ and $E_n \subset A$ be an (n, ε)-separated set. For each $I \subset J=\{j_1, \ldots, j_q\}$ and each $x \in E_n$ we define the specification $s(x, I)$ by requiring that it be an M-delayed specification with

$$\text{Tim}\, s(x, I) = \Big([0, n) \setminus \bigcup_{j_i \in I} [j_i-M, j_i+M]\Big) \cup I,$$

$$P_{s(x,I)}(t) = f^t(x) \quad \text{for } t \notin I \quad \text{and} \quad P_{s(x,I)}(j_i) = w_{j_i} \quad \text{for } j_i \in I.$$

Set $d=n+m$. By Theorem 2.10 choose

$$p(x, I) \in U(s(x, I), \tfrac{1}{2}\varepsilon) \cap \text{Per}_d\,(X).$$

Let $F_I=\{p(x, I) : x \in E_n\}$. If $I_1 \neq I_2$ and $x, y \in E_n$, then $s(x, I_1)$ and $s(y, I_2)$ are ε-separated; for if $j_i \in I_1 \setminus I_2$, then $j_i \in \text{Tim}\, s(x, I_1) \cap \text{Tim}\, s(y, I_2)$ and

$$d(P_{s(x,I_1)}(j_i), P_{s(y,I_2)}(j_i)) = d(w_{j_i}, f^{j_i}(y)) > \varepsilon.$$

By lemma (i) we have $p(x, I_1) \neq p(y, I_2)$; thus $I_1 \neq I_2$ implies $F_{I_1} \cap F_{I_2} = \varnothing$.

Suppose $z=p(x, I)=p(y, I)$ and $x \neq y$. For $t \in \text{Tim}\, s(x, I) \setminus I$, we have $P_{s(x,I)}(t) = f^t(x)$ and $P_{s(y,I)}(t)=f^t(y)$; so $d(f^t(z), f^t(x))<\frac{1}{2}\varepsilon$ and $d(f^t(z), f^t(y))<\frac{1}{2}\varepsilon$, hence $d(f^t(x), f^t(y))<\varepsilon$. Since $x, y \in E_n$, an (n, ε)-separated set, we must have $d(f^t(x), f^t(y))>\varepsilon$ for some

$$t \in [0, n) \setminus (\text{Tim}\, s(x, I) \setminus I) = \bigcup_{j_i \in I} [j_i-M, j_i+M].$$

By the proof of 3.2(iii), $\{x \in E_n : p(x, I)=z\}$ has at most $g^{\text{card} I}$ elements where $g=N(2M+1, \frac{1}{2}\varepsilon)$. Thus F_I has at least card $E_n \backslash g^{\text{card} I}$ elements.

As the F_I's are disjoint

$$N_d(f) \geqq \sum_{I \subset J} \text{card } F_I \geqq \sum_{I \subset J} \frac{1}{g^{\text{card} I}} \text{card } E_n$$
$$\geqq \sum_{r=0}^{\text{card} J} \binom{\text{card } J}{r} \frac{1}{g^r} \text{card } E_n = \left(1+\frac{1}{g}\right)^{\text{card} J} \text{card } E.$$

Since $2\varepsilon < \delta^*$, by 3.2(i) and 3.2(iii)

$$N_d(f) = N_{n+m}(f) \leqq N(n+M, 2\varepsilon) \leqq N(n, \varepsilon)N(M, \varepsilon).$$

Also card $J=q \geqq m/(2M+1)$. Thus

$$N(n, \varepsilon, A) = \text{card } E_n \leqq \frac{N(M, \varepsilon)}{[(1+1/g)^{1/2M+1}]^m} N(n, \varepsilon).$$

4. **Topological entropy.** Suppose $\mathscr{A}$ is a finite open cover of X. $E \subset \mathscr{A} \times \cdots \times \mathscr{A}$ (n-times) is an *n-cover* for $(f, \mathscr{A})$ if for every $z \in X$ there is an $(A_0, \ldots, A_{n-1}) \in E$ such that $f^k(x) \in A_k$ for all $0 \leqq k < n$. Let $M_n(f, \mathscr{A})$ denote the minimum cardinality of an n-cover for $(f, \mathscr{A})$. Then (see Adler, Konheim and McAndrew [1]) the limit

$$h(f, \mathscr{A}) = \lim_{n \to \infty} \frac{1}{n} \log M_n(f, \mathscr{A})$$

exists and the *topological entropy* of f is defined by

$$h(f) = \sup_{\mathscr{A}} h(f, \mathscr{A}).$$

(The above definitions and 4.1 and 4.2 below do not depend on our standing hypothesis that f satisfies Axiom A*; they work for any continuous map of a compact Hausdorff space.)

(4.1) DEFINITION. $f: X \to X$ has *completely positive topological entropy* (c.p.t.e.) if $h(f, \{C, D\}) > 0$ whenever $\{C, D\}$ is an open cover of X with $\bar{C} \neq \bar{X} \neq \bar{D}$.

(4.2) PROPOSITION. *Suppose $f: X \to X$ has c.p.t.e. Then $h(f) > 0$ unless X is a single point, and it is topologically transitive. If $g: Y \to Y$ and $h: X \to Y$ are continuous maps with h surjective and $g \circ h = h \circ f$, then g has c.p.t.e.*

Proof. Unless X is a single point an open cover $\{C, D\}$ as in 4.1 can be found and so $h(f) > 0$.

If f is not transitive, then there is an open set $C \neq \varnothing$ with $f^{-1}(C) \subset C$ and $\bar{C} \neq X$. Let $B \neq \varnothing$ be open with $\bar{B} \subset C$ and set $D = X \backslash \bar{B}$. Then $\{C, D\}$ is as above. Let

$$E_n = \{(\underbrace{C, \ldots, C}_{i \text{ times}}, \underbrace{D, \ldots, D}_{j \text{ times}}) : i+j = n, i, j \geqq 0\}.$$

We claim E_n is an n-cover for $(f, \{C, D\})$. For, if $x \in X$, then either $f^k(x) \in D$ for all $0 \leqq k < n$ or there is a largest k, denoted $k(x)$, such that $0 \leqq k < n$ and $f^k(x) \notin D$.

In the latter case $f^{k(x)}(x) \in C$ and so $f^m(x) \in C$ for all $m \leqq k(x)$ as $f^{-1}(C) \subset C$; $f^m(x) \in D$ for $m > k(x)$. As card $E_n = n+1$, $M_n(f, \{C, D\}) \leqq n+1$ and $h(\{C, D\}) = 0$— a contradiction.

Suppose $\{C, D\}$ is an open cover of Y with $\bar{C} \neq \bar{Y} \neq \bar{D}$. Then $\{h^{-1}(C), h^{-1}(D)\}$ satisfies the condition of 4.1 also. h and h^{-1} induce a bijection between n-covers for $(f, \{h^{-1}(C), h^{-1}(D)\})$ and $(g, \{C, D\}) = h(f_1\{h^{-1}(C), h^{-1}(D)\}) > 0$.

(4.3) THEOREM. *If $f: X \to X$ is C-dense, then f has c.p.t.e.*

Proof. Let $\{C, D\}$ be a cover as in 4.1. Choose $\varepsilon > 0$ and $p, q \in X$ such that $B_\varepsilon(p) \subset C \setminus D$ and $B_\varepsilon(q) \subset D \setminus C$. Let $M(\varepsilon)$ be the integer given by 2.10; set $N = M(\varepsilon) + 1$. Then $\tau_n = \{\{kN\} : 0 \leqq k < n\}$ is $M(\varepsilon)$-delayed.

For $(a_0, \ldots, a_{n-1}) \in \prod_{k=0}^{n-1} \{p, q\}$ define a specification $s = s_n(a_0, \ldots, a_{n-1})$ by $\tau(s) = \tau_n$ and $P_s(kN) = a_k$. By 2.10 choose points

$$x_n(a_0, \ldots, a_{n-1}) \in U(s_n(a_0, \ldots, a_{n-1}), \varepsilon).$$

Let E_n be an nN-cover for $(f, \{C, D\})$; for $x \in X$ let $F_n(x) = (F_n^0(x), \ldots, F_n^{nN-1}(x)) \in E_n$ be such that $f^j(x) \in F_n^j(x)$ for $0 \leqq j < nN$. Suppose $(a_0, \ldots, a_{n-1}) \neq (b_0, \ldots, b_{n-1})$; say $a_k = p$ and $b_k = q$. Then

$$f^{kN}(x_n(a_0, \ldots, a_{n-1})) \in B_\varepsilon(p) \leqq C \setminus D$$

and so $F_n^{kN}(x_n(a_0, \ldots, a_{n-1})) = C$; similarly $F_n^{kN}(x_n(b_0, \ldots, b_{n-1})) = D$ and so $F_n(x_n(b_0, \ldots, b_{n-1})) \neq F_n(x_n(a_0, \ldots, a_{n-1}))$. It follows that card $E_n \geqq 2^n$ and $M_{nN}(f, \{C, D\}) \geqq 2^n$; thus

$$h(f, \{C, D\}) \geqq \lim \frac{1}{nN} \log 2^n = \frac{1}{N} \log 2 > 0.$$

(4.4) REMARK. Now $f: X \to X$ satisfying Axiom A* could not be topologically transitive unless the permutation g in its C-dense decomposition (2.7) is a cycle, i.e. if the decomposition $X = X_1 \cup \cdots \cup X_m$ satisfies $X = \bigcup f^k X_1$; with 4.2 and 4.3 one sees that this is a sufficient condition for transitivity. It is now clear how 2.7 is just another version of Smale's Spectral Decomposition [16, p. 777]. We also see that $h(f) > 0$ unless X is finite; this result was proved before in [6]. The following is an improvement of the main result of [6].

(4.5) THEOREM. *If $f: X \to X$ is C-dense, then*

$$h(f) = \lim_{n \to \infty} \frac{1}{n} \log N_n(f).$$

Proof. Let $\mathscr{A}$ be a finite open cover of X with diam $(A) < \delta^*$ for all $A \in \mathscr{A}$ and let $\beta > 0$ be a Lebesgue number for $\mathscr{A}$ (i.e. every closed β-ball $B_\beta(x)$ lies inside some member of $\mathscr{A}$).

Let Q be a maximal (n, β)-separated set. For $z \in Q$ choose $B(z) = (A_0(z), \ldots, A_{n-1}(z))$ with $A_k(z) \in \mathscr{A}$ and

$$A_k(z) \supset \mathrm{Cl}\,(B_\beta(f^k(z))) \quad \text{for all } 0 \leqq k < n.$$

We claim $E_n=\{B(z) : z \in Q\}$ is an n-cover for $(f, \mathscr{A})$. For each $x \in X$ there is a $z_x \in Q$ for which $d(f^k(x), f^k(z_k)) \leqq \beta$ for all $0 \leqq k < n$; otherwise $Q \cup \{x\}$ would be an (n, β)-separated set bigger than Q. Since $f^k(x) \in A_k(z_x)$, E_n is an n-cover. We have shown $M_n(f, \mathscr{A}) \leqq N(n, \beta)$.

Let E be an n-cover for $(f, \mathscr{A})$ and R an (n, δ^*)-set. For $x \in R$ choose $g(x) = (A_0(x), \ldots, A_{n-1}(x)) \in E$ such that $f^k(x) \in A_k(x)$ for all $0 \leqq k < n$. If $g(x) = g(y)$, then $A_k(x) = A_k(y)$ and $d(f^k(x), f^k(y)) \leqq \operatorname{diam} A_k(x) < \delta^*$ for $0 \leqq k < n$; $x = y$ as R is an (n, δ^*)-separated set. As $g\colon R \to E$ is injective, card $E \geqq$ card R and $M_n(f, \mathscr{A}) \geqq N(n, \delta^*) \geqq N_n(f)$.

By 3.9(i) there is an $S > 0$ and n_0 such that $N_n(f) \geqq SN(n, \beta)$ for $n \geqq n_0$. Hence $SM_n(f, \mathscr{A}) \leqq N_n(f) \leqq M_n(f, \mathscr{A})$ for all $n \geqq n_0$. Since $(1/n) \log M_n(f, \mathscr{A})$ approaches the limit $h(f, \mathscr{A})$, so does $(1/n) \log N_n(f)$. As this is true for every $\mathscr{A}$ with diam $\mathscr{A} < \delta^*$ and in calculating $h(f)$ we need only consider $h(f, \mathscr{A})$ with $\mathscr{A}$ having small diameter,

$$h(f) = h(f, \mathscr{A}) = \lim_{n \to \infty} \frac{1}{n} \log N_n(f).$$

(4.6) Remark. Let

$$\gamma_f(\varepsilon) = \lim \sup \frac{1}{n} \log N(n, \varepsilon).$$

The proof above shows that, for any map f a compact metric space, $h(f) = \lim_{\varepsilon \to 0} \gamma_f(\varepsilon)$. Suppose f is a homeomorphism and δ is an expansive constant; if $\varepsilon \leqq \delta$, then 3.2(ii) goes through, i.e.

$$N(n, \delta) \leqq N(n, \varepsilon) \leqq N(n+m_\varepsilon, \delta)$$

for some m_ε, and so $\gamma_f(\varepsilon) = \gamma_f(\delta)$. In this case we have $\gamma_f(\delta) = h(f)$.

(4.7) Theorem. *Suppose $f\colon X \to X$ is C-dense and $A \subset X$ is closed with $\varnothing \neq A \neq X$ and $f(A) = A$. Then $h(f|A) < h(f)$.*

Proof. By the remark above, $h(f|A) = \gamma_{f|A}(\varepsilon)$ for $\varepsilon \leqq \delta^*$. Choose $w \in X \backslash A$ and $\varepsilon > 0$ so small that $A \cap B_\varepsilon(w) = \varnothing$. Recall 3.11, $N(n, \varepsilon, A) \leqq c_\varepsilon \tau_\varepsilon^m$, for $n > m$ where $\tau_\varepsilon < 1$. Then

$$\begin{aligned} \gamma_{f|A}(\varepsilon) &= \limsup_{n \to \infty} \frac{1}{n} \log N(n, \varepsilon, A) \\ &\leqq \lim_{n \to \infty} \frac{1}{n} \log c_\varepsilon \tau_\varepsilon^{n-1} N(n, \varepsilon) \\ &\leqq \log \tau_\varepsilon + \gamma_f(\varepsilon) = \log \tau_\varepsilon + h(f) < h(f). \end{aligned}$$

5. **Construction of a measure.** Let ψ be a countable base for the topology of X which is closed under finite union. Assume $\omega\colon \psi \to R$ satisfies, for $B \in \psi$,

$$\omega(B) \geqq 0, \qquad \omega(X) = 1,$$

$$\omega(B_1) \geqq \omega(B_2) \quad \text{when } B_1 \supset B_2,$$

$$\omega(B_1 \cup \cdots \cup B_n) \leqq \sum \omega(B_i),$$

and

$$\omega(B_1 \cup B_2) = \omega(B_1)+\omega(B_2) \quad \text{when } \bar{B}_1 \cap \bar{B}_2 = \varnothing.$$

For U open in X define $m(U)=\sup\{\omega(B): \bar{B}\subset U \text{ and } B \in \psi\}$.

(5.1) LEMMA. *If $U\subset\bigcup_{i=1}^{\infty} U_i$, then $m(U)\leqq\sum m(U_i)$. If $U\cap V=\varnothing$, then $m(U\cup V)=m(U)+m(V)$.*

Proof. Let $B\in\psi$ with $\bar{B}\subset U$. By compactness let $U_1, \ldots, U_n$ cover B. For $x\in\bar{B}$ choose $B_x\in\psi$ so that $\bar{B}_x\subset U_i$ for some i satisfying $1\leqq i\leqq n$. Let $B_{x_1}, \ldots, B_{x_r}$ cover $\bar{B}$ and set $A_i=\bigcup\{B_{x_j} : \bar{B}_{x_j}\subset U_i\}$. Then

$$\omega(B) \leqq \omega\left(\bigcup_{i=1}^{n} A_i\right) \leqq \sum_{i=1}^{n}\omega(A_i) \leqq \sum_{i=1}^{n} m(U_i).$$

Now vary B.

By the first part of the lemma, $m(U\cup V)\leqq m(U)+m(V)$. Suppose $B_1, B_2\in\psi$ with $\bar{B}_1\subset U$ and $\bar{B}_2\subset V$. Then $\mathrm{Cl}(B_1\cup B_2)\subset U\cup V$ and $\bar{B}_1\cap\bar{B}_2=\varnothing$; so

$$m(U\cup V) \geqq \omega(B_1\cup B_2) = \omega(B_1)+\omega(B_2).$$

Varying the B_i we obtain $m(U\cup V)\geqq m(U)+m(V)$.

For any $E\subset X$ we define

$$m(E) = \inf\{m(U) : U\supset E, U \text{ open}\}.$$

One sees easily that this definition agrees with the earlier one on open sets and that $m(K)=\inf\{\omega(B) : B\supset K, B\in\psi\}$ when K is closed. We let

$$\mathscr{M} = \{E\subset X : m(E) = \sup\{m(K) : K\subset E, K \text{ closed}\}\}.$$

With standard arguments we get

(5.2) PROPOSITION. *$\mathscr{M}=\mathscr{M}_{\psi,\omega}$ is a σ-field containing the Borel sets of X and $m=m_{\psi,\omega}$ is a complete normalized regular measure on $\mathscr{M}$.*

Proof. One can, for example, use 5.1 and imitate the proof of the Riesz Representation Theorem given in Rudin [19, p. 40].

(5.3) LEMMA. *If $\omega_1:\psi_1\to R$ and $\omega_2:\psi_2\to R$ are as above and there is a $K>0$ such that $\omega_2(B_2)\geqq K\omega_1(B_1)$ when $B_2\supset\bar{B}_1$ and $\omega_1(B_1)\geqq K\omega_2(B_2)$ when $B_1\supset\bar{B}_2$, then $\mathscr{M}_{\psi_1,\omega_1}=\mathscr{M}_{\psi_2,\omega_2}$ and $Km_{\psi_1,\omega_1}\leqq m_{\psi_2,\omega_2}\leqq(1/K)m_{\psi_1,\omega_1}$.*

Proof. For U open and $\bar{B}_1\subset U$ with $B_1\in\psi_1$ we can find $B_2\in\psi_2$ such that $\bar{B}_1\subset B_2\subset\bar{B}_2\subset U$. Hence $m_{\psi_2,\omega_2}(U)\geqq\omega_2(B_2)\geqq K\omega_1(B_1)$. Varying B_1, $m_{\psi_2,\omega_2}(U)\geqq Km_{\psi_1,\omega_1}(U)$. Similarly $m_{\psi_1,\omega_1}(U)\geqq Km_{\psi_2,\omega_2}(U)$. These inequalities extend to any $E\subset X$.

Suppose $E\in\mathscr{M}_{\psi_1,\omega_1}$. Letting $K_n\subset E$ be compact with $m_{\psi_1,\omega_1}(K_n)\geqq m_{\psi_1,\omega_1}(E)-1/n$ we see that $E=E_1\cup\bigcup_{n=1}^{\infty}K_n$ where $E_1\subset F$ for some Borel set F with $m_{\psi_1,\omega_1}(F)=0$. Then $m_{\psi_1,\omega_1}(F)=0$ also and $E_1\in\mathscr{M}_{\psi_2,\omega_2}$ since m_{ψ_2,ω_2} is complete. As ψ_2, ω_2

contains Borel sets, we finally see that $E \in \mathscr{M}_{\psi_2,\omega_2}$. The proof of $\mathscr{M}_{\psi_1,\omega_1} \subset \mathscr{M}_{\psi_2,\omega_2}$ is the same.

We will now see how to define some ω's when we are given a homeomorphism $f: X \to X$ which is C-dense. Let ψ be any base as above. By diagonalization we can find increasing sequences of integers $\{n_k\}$ such that

$$\omega(B) = \alpha_{\{n_k\}}(B) = \lim_k \frac{N_{n_k}(B)}{N_{n_k}(f)}$$

exists for every $B \in \psi$. The measure we obtain we denote by $\mu_{f,\{n_k\}}$. Lemma 5.3 (with $K=1$) shows us that the measure does not depend on the base used.

Let μ_n be the measure obtained by giving each point of $\mathrm{Per}_n(X)$ measure $1/N_n(f)$. Then $\mu_{n_k} \to \mu_{f,\{n_k\}}$ weakly (see Corollary 6.7).

(5.4) THEOREM. *Suppose $f: X \to X$ is C-dense. The measures $\mu_{f,\{n_k\}}$ are all equivalent in the sense of* 5.3. *They are positive on nonempty open sets and $\mu_{f,\{n_k\}}(\{x\})=0$ unless $X=\{x\}$. f is an automorphism of $(\mathscr{M}, \mu_{f,\{n_k\}})$.*

Proof. Let $\mu_{f,\{n_k\}}$ and $\mu_{f,\{m_k\}}$ be defined using bases Ψ_1 and Ψ_2 respectively. By 3.9(iii) there is a $K^*>0$ such that, if $B_1 \supset \bar{B}_2$, then

$$\alpha_{\{n_k\}}(B_1) \geqq \varphi(B_1) \geqq K^*\theta(B_2) \geqq \alpha_{\{n_k\}}(B_2).$$

5.3 gives equivalence.

If $U \neq \varnothing$ is open, then $U \supset \bar{B} \neq \varnothing$ for some $B \in \Psi$. Then, using 3.9(ii), $\mu_{f,\{n_k\}}(U) \geqq \alpha_{\{n_k\}}(B) \geqq \varphi(B) > 0$. Suppose $x \in X$ but $X \neq \{x\}$. Let

$$U_m = \{y \in X : d(f^k(y), f^k(x)) < \tfrac{1}{2}\delta^* \text{ for } 0 \leqq k \subset m\}.$$

Let $B_m \in \Psi$ with $x \in B_m \subset U_m$. Then $\mu_{f,\{n_k\}}(\{x\}) \leqq \alpha_{\{n_k\}}(B_m) \leqq \theta(U_m)$. By 3.9(b) there are m_0 and $S>0$ with $\theta(U_m) \leqq 1/sN_m(f)$ for all $m \geqq m_0$. By 4.3 and 4.2

$$h(f) = \lim \frac{1}{m} \log N_m(f) > 0.$$

Thus $N_m(f) \to \infty$, $\theta(U_m) \to 0$ and $\mu_{f,\{n_k\}}(\{x\})=0$.

Now Ψ, $\alpha_{\{n_k\}}$ and $f\Psi$, $\alpha_{\{n_k\}}$ clearly satisfy the hypotheses of 5.3 with $K=1$ (by the obvious and crucial fact that f permutes $\mathrm{Per}_n(X)$). Hence

$$f\mu_{f,\{n_k\}} = fm_{\Psi,\alpha_{\{n_k\}}} = m_{f\Psi,\alpha_{\{n_k\}}} = m_{\Psi,\alpha_{\{n_k\}}} = \mu_{f,\{n_k\}}.$$

(5.5) REMARK. Above we assumed $f: X \to X$ is C-dense. Suppose $f: X \to X$ satisfying Axiom A* is only assumed to be topologically transitive. Then $X = X_1 \cup \cdots \cup X_m$ with $f(X_i) = X_{i+1}$ $(X_{m+1} = X_1)$ and $f^m: X_1 \to X_1$ C-dense. From an invariant measure μ for $f^m: X_1 \to X_1$ we get one μ' for $f: X \to X$ by defining $\mu'(f^nE) = \mu(E)/m$ for $E \subset X_1$ measurable. This gives a bijection between invariant Borel measures for $f^m: X_1 \to X_1$ and $f: X \to X$. One sees that μ' is ergodic if and only if μ is, $h(f^m|X_1) = mh(f)$ and $h_\mu(f^m|X_1) = mh_{\mu'}(f)$. The measures defined above, in terms of periodic points of $f^m|X$, correspond to measures on X defined in terms of periodic points of f: $X \to X$. We shall study the C-dense case and this will give us results also for the general transitive case.

6. **Ergodicity and equality of measures.**

(6.1) DEFINITION. f is said to be *partially mixing* with respect to the f-invariant measure μ if there is an $R>0$ such that for any $E, F \in \mathcal{M}$,

$$\liminf_{n\to\infty} \mu(E \cap f^{-n}F) \geqq R\mu(E)\mu(F).$$

If $c_1 < c_2 < \cdots < c_r$ are integers, set $I(c_1, \ldots, c_r) = \min_i (c_{i+1} - c_i)$. f is *partially mixing in order r* if there is an $R_r > 0$ such that, if $E_1, \ldots, E_r \in \mathcal{M}$ and $I(c_1^n, \ldots, c_r^n) \to \infty$ as $n \to \infty$, then

$$\liminf_{n\to\infty} \mu(f^{-c_1^n}E_1 \cap \cdots \cap f^{-c_r^n}E_r) \geqq R_r\mu(E_1)\cdots\mu(E_r).$$

Notice that partially mixing is a stronger condition than ergodicity or weak mixing.

(6.2) THEOREM. *If f: $X \to X$ is C-dense, then f is partially mixing in all orders with respect to each $\mu = \mu_{f,\{n_k\}}$.*

Proof. Let $I(c_1^n, \ldots, c_r^n) \to \infty$. Let $\alpha = \frac{1}{8}\delta^*$; by 3.9(i) choose n_0 and $S>0$ so that $N_n(f) \geqq SN(n, 2\alpha)$ for all $n \geqq n_0$.

Suppose $E_1, \ldots, E_r$ are closed and $V_i \supset E_i$ with $V_i \in \Psi$. Choose $\varepsilon > 0$ so that $B_\varepsilon(E_i) \subset V_i$. Choose k large enough so that $n_k > 2D(\varepsilon)$ (see 2.4) and n so that $I(c_1^n, \ldots, c_r^n) > M(\alpha) + n_k$. Let $\tau_i = \{[c_i^n - D(\varepsilon), c_i^n + n_k - D(\varepsilon))\}$ and for $x \in \mathrm{Per}_{n_k}(V_i)$ define the specification s_x by $\tau(s_x) = \tau_i$ and $P_{s_x}(t) = f^{t-c_i^n}(x)$; let $A_i = \{s_x : x \in \mathrm{Per}_{n_k}(V_i)\}$. One notes now that $B = A_1 \wedge \cdots \wedge A_r$ is an 8α-separated s-set which is $M(\alpha)$-delayed. Also, by 2.4, we get

$$U(B, \alpha) \subset \bigcap_{i=1}^r f^{-c_i^n}B_\varepsilon(E_i) \subset \bigcap_{i=1}^r f^{-c_i^n}V_i.$$

By 3.7, we get

$$N_d\left(\bigcap f^{-c_i^n}V_i\right) \geqq N_d(U(B, \alpha)) \geqq \frac{K(r, \alpha)\,\mathrm{card}\,(B)\, N(d, \delta^*)}{N(rn_k, \frac{1}{2}\delta^*)}$$

for d sufficiently large. Now

$$N(d, \delta^*) \geqq N_d(f), \quad \mathrm{card}\,(B) = \prod N_{n_k}(V_i)$$

and, using 3.2(iii),

$$N(rn_k, \tfrac{1}{2}\delta^*) \leqq N(n_k, \tfrac{1}{4}\delta^*)^r \leqq N_{n_k}(f)^r/S^r.$$

Combining all these,

$$\frac{N_d(\bigcap f^{-c_i^n}V_i)}{N_d(f)} \geqq R_r \prod \frac{N_{n_k}(V_i)}{N_{n_k}(f)}$$

where $R_r = K(r, \alpha)S^r > 0$. Letting $d \to \infty$,

$$\varphi(\bigcap f^{-c_i^n} V_i) = \liminf_{d\to\infty} \frac{N_d(\bigcap f^{-c_i^n} V_i)}{N_d(f)} \geqq R_r \prod \frac{N_{n_k}(V_i)}{N_{n_k}(f)}.$$

This being true for all big n,

$$\liminf_{n\to\infty} \varphi(\bigcap f^{-c_i^n} V_i) \geqq R_r \prod \frac{N_{n_k}(V_i)}{N_{n_k}(f)}.$$

Letting $n_k \to \infty$,

$$\liminf_{n\to\infty} \varphi(\bigcap f^{-c_i^n} V_i) \geqq R_r \prod \alpha_{\{n_k\}}(V_i) \geqq R_r \prod \mu(E_i).$$

Now suppose $V_i^1 \supset E_i$ open and choose the V_i above so that $V_i^1 \supset \bar{V}_i$. Then

$$\bigcap_i f^{-c_i^n} V_i^1 \supset \mathrm{Cl}\left(\bigcap_i f^{-c_i^n} V_i\right).$$

Choose $B \in \Psi$ so that

$$\bigcap f^{-c_i^n} V_i^1 \supset \bar{B} \supset \bigcap f^{-c_i^n} V_i.$$

Then

$$\mu(\bigcap f^{-c_i^n} V_i^1) \geqq \alpha_{\{n_k\}}(B) \geqq \varphi(\bigcap f^{-c_i^n} V_i)$$

and

$$\liminf_{n\to\infty} \mu(\bigcap f^{-c_i^n} V_i^1) \geqq R_r \prod \mu(E_i).$$

Now

$$\mu(\bigcap f^{-c_i^n} E_i) \geqq \mu(\bigcap f^{-c_i^n} V_i^1) - \sum \mu(V_i^1 \backslash E_i).$$

Letting $\mu(V_i \backslash E_i) \to 0$ we get

$$\liminf_{n\to\infty} \mu(\bigcap f^{-c_i^n} E_i) \geqq R_r \prod \mu(E_i).$$

For any $E_i^* \in \mathscr{M}$ consider $E_i \in E_i^*$ closed. Then

$$\liminf_{n\to\infty} \mu(\bigcap f^{-c_i^n} E_i^*) \geqq \liminf_{n\to\infty} \mu(\bigcap f^{-c_i^n} E_i) \geqq R_r \prod \mu'(E_i).$$

Now let $\mu(E_i) \to \mu(E_i^*)$.

(6.3) Corollary. *Suppose $f\colon X \to X$ satisfying Axiom* A* *is topologically transitive. Then the measure μ^* on X corresponding to $\mu_{f^m,\{n_k\}}$ on one of its C-dense factors is ergodic under f.*

Proof. See Remark 5.5.

The following standard fact was pointed out to us by W. Parry.

(6.4) Lemma. *Suppose $f\colon X \to X$ is an ergodic automorphism of two equivalent normalised Borel measures m_1 and m_2. Then $m_1 = m_2$.*

Proof. Let dm_1/dm_2 denote the Radon-Nikodym derivative. It is f-invariant, hence a constant (clearly 1) by ergodicity.

(6.5) THEOREM. *Let $f: X \to X$ be C-dense. Then all the $\mu_{f,\{n_k\}}$ have a common value μ_f.*

Proof. 5.4, 6.2, and 6.4.

(6.6) THEOREM. *Let $f: X \to X$ be C-dense. If K is closed and $\mu_f(K)=0$, then*

$$\lim_{n\to\infty} (N_n(K)/N_n(f)) = 0.$$

If U is open with $\mu_f(\partial U)=0$, then $\lim (N_n(U)/N_n(f))=\mu_f(U)$.

Proof. Suppose $\{m_j\}$ is an increasing sequence of integers so that either

$$N_{m_j}(K)/N_{m_j}(f) \to a > 0 \quad \text{or} \quad N_{m_j}(U)/N_{m_j}(f) \to b \neq \mu_f(U).$$

Let ψ be a countable base closed under finite union and $\{n_k\}$ a subsequence of $\{m_j\}$ so that $\mu_{f,\{n_k\}}$ is defined with ψ.

Suppose $N_{m_j}(K)/N_{m_j}(f) \to a>0$. If $B\supset K$, $B \in \psi$, then

$$\alpha_{\{n_k\}}(B) = \lim \frac{N_{n_k}(B)}{N_{n_k}(f)} \geqq \lim \frac{N_{n_k}(K)}{N_{n_k}(f)} = a.$$

It follows that $\mu_f(K)=\inf \alpha_{\{n_k\}}(B)\geqq a>0$, a contradiction. Suppose $N_{m_j}(U)/N_{m_j}(f) \to b\neq\mu_f(U)$. For $B\supset \bar{U}$, $B\in\psi$ we have $\alpha_{\{n_k\}}(B)\geqq b$; hence $\mu_f(\bar{U})=\mu_{f,\{n_k\}}(\bar{U})\geqq b$. For $\bar{B}\subset U$, $B\in\psi$, we have $\alpha_{\{n_k\}}(B)\leqq b$; hence $\mu_f(U)\leqq b$. As $\mu_f(\partial U)=0$, $b\geqq\mu_f(U) =\mu_f(\bar{U})=b$ and so $\mu_f(U)=b$, a contradiction.

(6.7) COROLLARY. *Let $f: X\to X$ be C-dense. Then, for any $F\in C(X)$,*

$$\frac{1}{N_n(f)} \sum_{x\in \mathrm{Per}_n(f)} F(x) \to \int F\, d\mu_f$$

as $n\to\infty$. (We say that μ_f is derived from f by periodic points to mean the above statement.)

Proof. Choose b such that $-b<F(x)<b$ for all $x\in X$. Let $\varepsilon>0$. Choose $-b =a_0<a_1<\cdots<a_r=b$ with $a_{i+1}-a_i<\varepsilon$, $\mu_f(\{x : F(x)=a_i\})=0$ and $F(x)=a_i$ for no periodic point x.

Let $U_i=\{x : a_{i-1}<F(x)<a_i\}$. Choose $N(\varepsilon)$ so big that

$$|(N_n(U_i)/N_n(f))-\mu_f(U_i)| < \varepsilon/b$$

for all $n\geqq N(\varepsilon)$ and each i. This is possible since $F(\partial U_i)\subset\{a_{i-1}, a_i\}$ and so $\mu_f(\partial U_i)=0$ by construction; hence 6.6 applies to U_i. We also have

$$\left| N_n(f)^{-1} \sum_{x\in\mathrm{Per}_n(f)} F(x) - \sum_{i=1}^{r} a_i(N_n(U_i)/N_n(f))\right| \leqq \varepsilon.$$

Putting our above two inequalities together one sees that

$$\left| N_n(f)^{-1} \sum_{x\in\mathrm{Per}_n(f)} F(x) - \sum a_i\mu_f(U_i)\right| \leqq 2\varepsilon.$$

Since $|\int F\,d\mu_f - \sum a_i\mu_f(U_i)| \leqq \varepsilon$, we finally get

$$\left|\int F\,d\mu_f - N_n(f)^{-1} \sum_{x\in \mathrm{Per}_n(f)} F(x)\right| \leqq 3\varepsilon$$

for all $n \geqq N(\varepsilon)$.

7. **The algebraic case.** Suppose $f\colon G\to G$ is an automorphism of an n-dimensional torus G. f is a *hyperbolic* if $Df\colon T_eG \to T_eG$ has no eigenvalues on the unit circle. Then (see [16]) f satisfies Axiom A* and is C-dense because G is connected (using 2.7). f of course preserves the normalized Haar measure m on G.

(7.1) PROPOSITION. *If f is a hyperbolic automorphism of a torus, then $\mu_f = m$.*

Proof. Suppose $g\in G$ and $E\subset G$ is closed. Let $\mu_f=\mu_{f,\{n_k\}}$ be defined via the base Ψ. Consider $B\in\Psi$ with $B\supset E+g$. There are $B^1\in\Psi$ and open V such that $B^1\supset E$, $g\in V$ and $B^1+V\subset B$. By 3.9(ii) there is an N such that $N_n(V)>0$ for all $n\geqq N$. For $n_k\geqq N$ and $g_{n_k}\in \mathrm{Per}_{n_k}(V)$ we have $g_{n_k}+\mathrm{Per}_{n_k}(B^1)\subset B$. If $x\in \mathrm{Per}_{n_k}(B^1)$, then as f is a group automorphism $f^{n_k}(g_{n_k}+x)=f^{n_k}(g_{n_k})+f^{n_k}(x)=g_{n_k}+x$; so $g_{n_k}+x\in\mathrm{Per}_{n_k}(B)$. Thus $N_{n_k}(B)\geqq N_{n_k}(B^1)$ for $n_k\geqq N$ and $\alpha_{\{n_k\}}(B)\geqq\alpha_{\{n_k\}}(B^1)\geqq\mu_{f,\{n_k\}}(E)$. Varying B, $\mu_{f,\{n_k\}}(g+E)\geqq\mu_{f,\{n_k\}}(E)$. Using $-g$ instead of g, $\mu_{f,\{n_k\}}(g+E)\leqq\mu_{f,\{n_k\}}(E)$. Thus $\mu_f(E)=\mu_f(g+E)$ for all $g\in G$ and E closed; it follows that μ_f is Haar measure.

Now let G be a torus acting freely on a compact metric space X (i.e. $g_1x=g_2x$ implies $g_1=g_2$) and let μ be normalized Haar measure on G. Let $\pi\colon X\to X_G=X/G$ be the projection map. Now suppose X_G has a normalized Borel measure m_G. Suppose $F\in C(X)$. If $\pi(x_1)=\pi(x_2)=y$, then

$$\int_G F(gx_1)\,d\mu = \int_G F(gx_2)\,d\mu$$

for $x_1=g_1x_2$ for some $g_1\in G$ and then $F(gx_1)=F(g_1gx_2)$ is obtained from $F(gx_2)$ (as a function on G) by translating the variable. Denote this common value by $H_F(y)$; $H_F\in C(X_G)$. Define a measure m on X by

$$\int_X F\,dm = \int_{X_G} H_F\,dm_G.$$

Now suppose $S\colon X\to X$ is a homeomorphism and $\sigma\colon G\to G$ an automorphism such that $S(gx)=\sigma(g)S(x)$. Then S induces a homeomorphism S_G of X_G such that $\pi\circ S=S_G\circ\pi$. If S_G preserves m_G, then S preserves m and we say (S, m) is a σ-*extension* of (S_G, m_G).

(7.2) PROPOSITION. *Let (S, m) be a σ-extension of (S_G, m_G) with σ a hyperbolic automorphism of the torus. If m_G is derived from S_G by periodic points, then m is derived from S by periodic points.*

Proof. Let $F\in C(X)$ and $\varepsilon>0$. Choose $x_1,\dots,x_s\in X$ such that for each $x\in X$

there is an x_i such that $|F(gx)-F(gx_i)| \leqq \varepsilon/3$ for all $g \in G$. Since μ is derived from σ by periodic points (see 6.7), there is an $N(\varepsilon)$ such that

$$\left| N_n(\sigma)^{-1} \sum_{g \in \mathrm{Per}_n(\sigma)} F(gx_i) - \int_G F(gx_i)\, d\mu \right| \leqq \varepsilon/3$$

for any $n \geqq N(\varepsilon)$. Combining the above inequalities we get

$$\left| N_n(\sigma)^{-1} \sum_{g \in \mathrm{Per}_n(\sigma)} F(gx) - \int_G F(gx)\, d\mu \right| \leqq \varepsilon$$

for any $x \in X$ and any $n \geqq N(\varepsilon)$.

Recall that $\int_X F\, dm = \int_{X_G} H_F\, dm_G$ where $H_F(\pi(x)) = \int_G F(gx)\, d\mu$. As m_G is derived from S_G by periodic points there is an $M \geqq N(\varepsilon)$ such that

$$\left| \int_{X_G} H_F\, dm_G - N_n(S_G)^{-1} \sum_{y \in \mathrm{Per}_n(S_G)} H_F(y) \right| \leqq \varepsilon$$

for any $n \geqq M$. At this stage of the proof we need the following.

LEMMA. *If $S_G^n(y)=y$, then $S^n(x)=x$ for some $x \in \pi^{-1}(y)$.*

Proof. Let $z \in \pi^{-1}(y)$. Then $S^n(z)=g_1 z$ for some $g_1 \in G$, $S^n(gz)=\sigma^n(g)g_1 z$. We want to solve $S^n(gz)=gz$ or $g=\sigma^n(g)g_1$. In additive notation $(\sigma^n - I)g = -g_1$. Since σ^n is hyperbolic, there is such a g. Let $x=gz$. By this lemma for $y \in \mathrm{Per}_n\,(S_G)$ choose $x_y \in \pi^{-1}(y) \cap \mathrm{Per}_n\,(S)$. Then

$$\left| H_F(y) - N_n(\sigma)^{-1} \sum_{g \in \mathrm{Per}_n(\sigma)} F(gx_y) \right| \leqq \varepsilon.$$

Now $gx_y \in \mathrm{Per}_n\,(S)$ if and only if $\sigma^n(g)x_y = \sigma^n(g)S^n(x_y) = S^n(gx_y) = gx_y$, i.e. if and only if $g \in \mathrm{Per}_n\,(\sigma)$. Thus

$$\mathrm{Per}_n\,(S) = \{gx_y : g \in \mathrm{Per}_n\,(\sigma),\, y \in \mathrm{Per}_n\,(S_G)\}$$

(for clearly $z \in \mathrm{Per}_n\,(S)$ implies $\pi(z) \in \mathrm{Per}_n\,(S_G)$). Thus

$$N_n(S_G)^{-1} \sum_{y \in \mathrm{Per}_n(S_G)} N_n(\sigma)^{-1} \sum_{g \in \mathrm{Per}_n(\sigma)} F(gx_y) = N_n(S)^{-1} \sum_{z \in \mathrm{Per}_n(S)} F(z).$$

Hence, as $\int_X F\, dm = \int_{X_G} H_F\, dm_G$, we have

$$\left| \int F\, dm - N_n(S)^{-1} \sum_{z \in \mathrm{Per}_n(S)} F(z) \right| \leqq 2\varepsilon$$

for all $n \geqq M$.

Suppose $f\colon N/\Gamma \to N/\Gamma$ is a hyperbolic automorphism of a nilmanifold (one can see [13] or [16] for the definition). Then N/Γ has a unique normalized Borel measure m which is invariant under the action of N; m is f-invariant. It is well known that (f, m) is obtained through a succession of extensions via hyperbolic toral automorphisms with a single point as the initial base space. By 7.2 we have that m is derived from f by periodic points.

(7.3) THEOREM. *If f is a hyperbolic automorphism of a nilmanifold, then $\mu_f = m$.*

Proof. f satisfies Axiom A* and is C-dense since N/Γ is connected (by 2.7). 6.7 says that μ_f is derived from f by periodic points. At most one measure can be derived from f by periodic points.

(7.4) REMARK. Conversations with W. Parry, S. Smale, and P. Walters were helpful in finding a proof for 7.3. Parry in particular pointed out how the periodic points of S are related to those of S_G and σ. Hyperbolic automorphisms of nilmanifolds thus distribute their periodic points uniformly with respect to the usual measure. For this particular case §§6 and 8 yield already known facts (see [2] or [13] for example).

8. **The entropy of μ_f.** We refer the reader to [5] for a definition of measure theoretic entropy.

(8.1) Suppose f: $X \to X$ satisfying Axiom A* is topologically transitive. Then $h_{\mu_f}(f) = h(f)$.

Proof. By 5.5 we may assume f is C-dense. Cover X by open sets $U_1, \ldots, U_r$ with diam $U_i < \delta^*$. Choose disjoint Borel sets $A_1, \ldots, A_r$ such that $U_i \supset \bar{A}_i$ and $X = \bigcup_{i=1}^r A_i$. In [8] L. Goodwyn shows that for any f-invariant normalized Borel measure ρ on X (and f: $X \to X$ any continuous map) we have $h_\rho(f) \leqq h(f)$. We complete our proof by showing the partition $\beta = \{A_1, \ldots, A_r\}$ satisfies $h_{\mu_f}(f, \beta) \geqq h(f)$. For any $1 \leqq i_0, \ldots, i_{m-1} \leqq r$ consider the sets

$$V = \bigcap_{k=0}^{m-1} f^{-k} U_{i_k} \supset \bigcap_{k=0}^{m-1} f^{-k} A_{i_k} = D(i_0, \ldots, i_{m-1}).$$

By 3.9(v) there are m_0 and $S > 0$ such that $\theta(V) \leqq 1/SN_m(f)$ for all $m \geqq m_0$. Then $\mu_f(D) \leqq \theta(V) \leqq 1/SN_m(f)$. Define the function

$$h_m = \frac{1}{m} \sum_{(i_0, \ldots, i_{m-1})} (-\log \mu_f(D))\chi_D$$

where χ_D is the characteristic function of D. For $m \geqq m_0$ we have

$$-\log \mu_f(D) \geqq \log S + \log N_m(f).$$

By definition

$$\int_{h_m} d\mu_f \to h_{\mu_f}(f, \beta)$$

as $n \to \infty$. Hence, using 4.5,

$$h_{\mu_f}(f, \beta) \geqq \lim \frac{1}{m} [\log N_m(f) + \log S] = h(f).$$

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University of Warwick,
Coventry, England