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## Welding Riemann Surfaces and Transmission Problems with Shifts

by DONALD ORTH<sup>1, 2)</sup>

I. A real, 2-dimensional  $C^\infty$  manifold  $X$  is called an  $H$ -manifold whenever there is a coordinate system on  $X$  for which  $\varphi_1 \circ \varphi_2^{-1}$  is either biholomorphic or biantiholomorphic on  $\varphi_2(U_1 \cap U_2)$  for every pair  $\varphi_1, \varphi_2$ . A closed subset  $S$  of  $X$  is called a  $C^{1+a}$  1-complex on  $X$  if  $S$  is locally a star of  $C^{1+a}$  curves and is equipped with its minimal simplicial structure ([6], [7]);  $S$  is not necessarily oriented. From the bordered  $H$ -manifold  $\bar{X}$  relative to  $X$  and  $S$  ([6], [7]). Intuitively this is done by cutting  $X$  along  $S$  and attaching to each resulting piece those 1-simplices of  $S$  which lie along it. Let  $\text{pr}$  be the projection of  $\bar{X}$  onto  $X$ ,  $\bar{X}_\beta = \text{pr}^{-1}(S)$ , and  $\{\sigma_\lambda^1: \lambda \in \Lambda\}$  the 1-simplices of a simplicial structure on  $\bar{X}_\beta$  for which  $\text{pr}(\sigma_\lambda^1)$  is a  $C^{1+a}$  curve on  $X$  for every  $\lambda \in \Lambda$  (or equivalently, the projection of this simplicial structure onto  $S$  refines the minimal structure on  $S$ ). Let  $\varphi: \Lambda \rightarrow \Lambda$  be a bijective map such that

- (i)  $\varphi(\lambda) \neq \lambda$ ;
- (ii)  $\varphi \circ \varphi(\lambda) = \lambda$

for every  $\lambda \in \Lambda$ . Let  $\alpha_\lambda: \sigma_\lambda^1 \rightarrow \sigma_{\varphi(\lambda)}^1$  be a  $C^{1+a}$  homeomorphism such that

$$\alpha_{\varphi(\lambda)} \circ \alpha_\lambda = \text{identity},$$

again for every  $\lambda \in \Lambda$ . Form the quotient space  $X^\alpha$  from  $\bar{X}$  by identifying two points  $\bar{x}, \bar{y} \in \bar{X}_\beta$  whenever there are finitely many maps  $\alpha_{\lambda_1}, \dots, \alpha_{\lambda_n}$  for which  $\alpha_{\lambda_n} \circ \dots \circ \alpha_{\lambda_1}(\bar{x}) = \bar{y}$ . Let  $\chi: \bar{X} \rightarrow X^\alpha$  be the quotient map. It will be assumed throughout that  $\chi^{-1}(x)$  is a finite set for every  $x \in X^\alpha$ .  $X^\alpha$  is then a smooth manifold. A condition on the maps  $\{\alpha_\lambda: \lambda \in \Lambda\}$  will be given and shown to be both necessary and sufficient in order that

- (a)  $X^\alpha$  can be given a unique  $H$ -structure for which

$$\chi \circ \text{pr}^{-1}: X \setminus S \rightarrow X^\alpha \setminus \chi(\bar{X}_\beta)$$

is an  $H$ -homeomorphism ( $X^\alpha$  is then said to be obtained uniquely from  $X$  by welding);

- (b)  $S^\alpha = \chi(\bar{X}_\beta)$  is a  $C^{1+a'}$  1-complex on  $X^\alpha$  for some  $a' \leq a$ .

This condition is described as follows. For simplicity, suppose that every point on  $S$  and  $S^\alpha$  has order  $> 1$  ([6]); the case when  $S$  or  $S^\alpha$  has points of order  $= 1$  will be discussed later. Let  $\bar{X}_j, j \in J$  denote the connected components of  $\bar{X}$  and  $\text{pr}_j$  the map  $\text{pr}|_{\bar{X}_j}$ . The  $H$ -coordinate system on  $\bar{X}$  can always be chosen so that for any

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coordinate neighborhood  $U$  of a point in  $\bar{X}_j \cap \bar{X}_\beta$  and its corresponding coordinate  $\bar{\varphi}$ ,  $\bar{\varphi}(U)$  is a wedge in  $\mathbb{C}$  with tip at the origin and  $\psi = \varphi \circ \text{pr}_j \circ \bar{\varphi}^{-1}$  is angle preserving on  $\bar{\varphi}(U)$ , where  $\varphi$  is a coordinate in an open set on  $X$  containing  $\text{pr}_j(U)$ . For any vertex  $x$  of  $\bar{X}_\beta$  and  $\sigma_x^1$  containing  $x = \bar{\varphi}_2 \circ \alpha_\lambda^{-1} \circ \bar{\varphi}_1^{-1}$  ( $\bar{\varphi}_1$  and  $\bar{\varphi}_2$  are coordinates at  $x$  and  $\alpha_\lambda(x)$  respectively) is a map from the ray  $\{te^{i\zeta}: 0 \leq t < M\}$  onto the ray  $\{te^{i\eta}: 0 \leq t < N\}$ . Define  $\alpha'_\lambda(t)$  by the rule  $\alpha'_\lambda(te^{i\zeta}) = \alpha'_\lambda(t)e^{i\eta}$ ;  $(d\alpha'_\lambda/dt)(0)$  exists and is nonzero. Denote  $(d\alpha'_\lambda/dt)(0)$  by  $\dot{\alpha}_\lambda(x)$ ;  $\dot{\alpha}_\lambda(x)$  depends on the choice of coordinates. Choose an oriented coordinate neighborhood of every point in  $S^a$  which is the image under  $\chi$  of a vertex of  $\bar{X}_\beta$ ; this orientation induces one on a coordinate neighborhood of every vertex  $x$  of  $\bar{X}_\beta$  and thereby an orientation on a piece of each of the two 1-simplices containing  $x$ .  $x$  is the initial point of one piece and the terminal point of the other. Denote the 1-simplex whose piece has  $x$  as initial point by  $\sigma_x^1$  and by  $\alpha_x$  the map  $\alpha_\lambda$  whose domain is  $\sigma_x^1$ . For each vertex  $x$  of  $\bar{X}_\beta$  the product  $\prod \{\dot{\alpha}_y(y): \chi(y) = \chi(x)\}$  is independent of the choice of coordinates. The condition referred to above is that for every vertex  $x \in \bar{X}_\beta$

$$\prod \{\dot{\alpha}_y(y): \chi(y) = \chi(x)\} = 1. \quad (1)$$

The condition is the same as (1) at a vertex  $x$  if we choose  $\sigma_x^1$  to be the simplex whose piece has  $y$  as its terminal point for every  $y$  for which  $\chi(y) = \chi(x)$ , and so is also independent of the above choice of oriented coordinate neighborhoods.

Using the welding procedure and the results of [6], it can be shown that there is a large class of transmission problems with shifts generalizing those in the sense of HASEMAN and CARLEMAN such that for each member of this class there is an associated holomorphic fibre bundle over a corresponding welded Riemann surface for which the solution space of the problem is functorially isomorphic to the space of global holomorphic sections in the associated bundle. Known results about holomorphic fibre bundles on Riemann surfaces can then be used to describe the solution spaces.

Finally, the welding and transmission problems on holomorphic families of Riemann surfaces are discussed.

*Notation.* A  $C^a$  map is one which is Hölder continuous with index  $a$ . It is  $C^{1+a}$  if it is continuously differentiable with  $C^a$  first partials. It is  $C_0^{1+a}$  if it is  $C^{1+a}$  with nowhere zero first partials. All curves are smooth, so a  $C^{1+a}$  curve is one described by a  $C_0^{1+a}$  map.  $G(K)$  denotes the disc in  $\mathbb{C}$  with center the origin and radius  $K$ , while  $\ell(\zeta, K)$  is the ray  $\{t \exp(i\zeta): 0 \leq t < K\}$ .  $D(K)$  and  $\bar{D}(K)$  denote wedges of the form  $\{w: |w| < K, \zeta < \arg w < \eta\}$  and  $\{w: |w| < K, \zeta \leq \arg w \leq \eta\}$  respectively.  $\mathbb{C}^+ = \{w: \text{Im } w \geq 0\}$ ,  $\mathbb{C}^- = \mathbb{C} \setminus \text{Int } \mathbb{C}^+$ .

## § 1. The Local Problem

Let  $\bar{X}$  be the disjoint union  $\cup \{\bar{D}_\mu(K_\mu): \mu = 1, \dots, n\}$ ; clearly  $\bar{X}_\beta = \cup \{b dy_{G(K_\mu)} \bar{D}_\mu(K_\mu): \mu = 1, \dots, n\}$ . Let  $\alpha_\mu$  be a  $C_0^{1+a}$  homeomorphism of  $\ell(\eta_\mu, K_\mu)$

onto  $\ell(\zeta_{\mu+1}, K_{\mu+1})$ . Form  $X^\alpha$  relative to  $\bar{X}_\beta$  and  $\{\alpha_\mu, \alpha_\mu^{-1} : \mu = 1, \dots, n\}$ .  $X^\alpha$  and  $S^\alpha$  have properties (a) and (b) of the introduction if and only if

1°) there is a region  $G$  in  $\mathbb{C}$  and a star of simple,  $C^{1+\alpha'}$  curves ([6])  $\{\mathcal{C}_\mu : \mu = 1, \dots, n\}$  at some point  $w_0 \in G$  which divides  $G$  into  $n$  simply-connected domains  $G_\mu$ , where  $\text{bdy}_G G_\mu = \mathcal{C}_{\mu-1} \cup \mathcal{C}_\mu$ ;

2°) there exist  $C^{1+\alpha'}$  homeomorphisms  $A_\mu : \bar{D}_\mu(K_\mu) \rightarrow Cl_G G_\mu$  which are biholomorphic on  $D_\mu(K_\mu)$  and satisfy

$$(i) \quad A_\mu(0) = w_0$$

$$(ii) \quad A_{\mu+1}^{-1} \circ A_\mu = \alpha_\mu \text{ on } \ell(\eta_\mu, K_\mu); \quad ^3)$$

3°) (uniqueness) if  $G_\mu^*, \mathcal{C}^*, A_\mu^*$  also satisfy 1° and 2°, then there is a homeomorphism  $\mathcal{L} : G \rightarrow G^*$  for which both  $\mathcal{L}$  and  $\mathcal{L}^{-1}$  are  $H$ -maps and  $A_\mu = \mathcal{L} \circ A_\mu^*$  for every  $\mu$ .

$X^\alpha$  and  $S^\alpha$  are said to have properties (a) and (b) *locally* if there is an open neighborhood  $V$  of  $\chi(0)$  in  $X^\alpha$  for which  $X^\alpha \cap V$  and  $S^\alpha \cap V$  have properties (a) and (b).

In order to prove the necessity of condition (1) for the local problem, let  $\alpha'_\mu$  be the real-valued function defined by

$$\alpha_\mu(t \exp(i\eta_\mu)) = \alpha'_\mu(t) \exp(i\zeta_{\mu+1}).$$

Define  $\zeta^{-1} = \sum_{\mu=1}^n (\eta_\mu - \zeta_\mu)$ ; a single-valued branch  $g_\mu$  of  $w^{2\pi\zeta}$  can be defined on each wedge  $\bar{D}_\mu(K_\mu)$ . Now

$$A_\mu^* = A_\mu \circ g_\mu^{-1} : g_\mu(\bar{D}_\mu(K_\mu)) \rightarrow G_\mu$$

is biholomorphic on  $g_\mu(D_\mu(K_\mu))$  and therefore  $C^{1+\alpha'}$  on  $g_\mu(\bar{D}_\mu(K_\mu))$ ;  $A_\mu^*$  is also angle preserving at the origin and so  $(d/dw) A_\mu^*$  exists on  $g_\mu(\bar{D}_\mu(K_\mu))$  and is nowhere zero. These facts are Kellogg's theorem ([3], [9]). It follows that  $(d/dw) (A_\mu^*)^{-1}$  exists and is nonzero on  $Cl_G G_\mu$ . Now

$$(A_{\mu+1}^*)^{-1} \circ A_\mu^* = g_{\mu+1} \circ A_{\mu+1}^{-1} \circ A_\mu \circ g_\mu^{-1} = g_{\mu+1} \circ \alpha_\mu \circ g_\mu^{-1} \quad ^3)$$

and so

$$\begin{aligned} \prod_{\mu=1}^n \left| \frac{d}{dt} \alpha'_\mu(0) \right| &= \prod \left| \frac{d}{dt} g_{\mu+1} \circ \alpha_\mu \circ g_\mu^{-1} \right|^{2\pi\zeta} \\ &= \prod \left| \frac{d}{dt} A_{\mu+1}^{*-1} \circ A_\mu^*(0) \right|^{2\pi\zeta} = \prod \left| \frac{d}{dw} A_{\mu+1}^{*-1}(0) \right|^{2\pi\zeta} \cdot \left| \frac{d}{dw} A_\mu^*(0) \right|^{2\pi\zeta} = 1; \end{aligned}$$

$(d/dt)$  means the following. The above maps, e.g.  $(A_{\mu+1}^*)^{-1} \circ A_\mu^*$ , are maps from one ray through the origin to another and so define real-valued functions of the real variable  $t$  just as  $\alpha_\mu$  defines  $\alpha'_\mu$ . It is these functions which are differentiated with respect to  $t$ . This proves the necessity of the condition.

<sup>3)</sup> Indices are taken modulo  $n$ .



Now assume that

$$\prod_{\mu=1}^n \left| \frac{d}{dt} \alpha'_\mu(0) \right| = 1; \quad (1')$$

since for  $\alpha_\mu^* = g_{\mu+1} \circ \alpha_\mu \circ g_\mu^{-1}$  we have

$$\prod_{\mu=1}^n \left| \frac{d}{dt} \alpha_{\mu'}^*(0) \right|^{2\pi\zeta} = \prod_{\mu=1}^n \left| \frac{d}{dt} \alpha'_\mu(0) \right| = 1 = \prod_{\mu=1}^n \left| \frac{d}{dt} \alpha_{\mu'}^*(0) \right|,$$

there is no loss in generality in assuming that  $\zeta^{-1} = 2\pi$ . Of course the wedges may be rotated so that  $\eta_\mu = \zeta_{\mu+1}$ .

(1.1) LEMMA. If  $a_\mu$  are positive numbers for which  $\prod_{\mu=1}^n a_\mu = 1$  ( $n > 1$ ), then there are positive numbers  $c_1, \dots, c_n$  satisfying  $c_{\mu+1}^{-1} \cdot a_\mu \cdot c_\mu = 1$  for all  $\mu$ .

*Proof.* Obvious.

Let  $c_\mu$  be the constants determined in the lemma for  $a_\mu = |(d/dt) \alpha'_\mu(0)|$ , and denote also by  $c_\mu$  the constant map on  $\mathbb{C}$  with value  $c_\mu$ . The maps  $\alpha_\mu^* = c_{\mu+1}^{-1} \circ \alpha_\mu \circ c_\mu$  satisfy  $|(d/dt) \alpha_{\mu'}^*(0)| = 1$ , and so there is no loss in generality in assuming that  $|(d/dt) \alpha'_\mu(0)| = 1$ . In fact, since the functions  $\alpha'_\mu$  are increasing, we may assume that

$$\frac{d}{dt} \alpha'_\mu(0) = 1. \quad (2)$$

Finally, it may be assumed that there is  $\mu$  and  $\nu$  with  $\mu \neq \nu$  and  $\zeta_\nu = \zeta_\mu + \pi$ . For if not, choose a  $\zeta_\mu$  and let  $\zeta_0 = \zeta_\mu + \pi$ ;  $\ell(\zeta_0, K_\nu)$  is contained in some  $D_\nu(K_\nu)$ . Form  $\overline{D_\nu(K_\nu)}$  relative to  $\ell(\zeta_0, K_\nu)$  and let  $\overline{D_1(K_\nu)} \cup \overline{D_2(K_\nu)} = \overline{D_\nu(K_\nu)}$ , while  $\alpha$  is the unique welding correspondence between  $\overline{D_1(K_\nu)}$  and  $\overline{D_2(K_\nu)}$  which induces in the obvious way the identity map on  $\ell(\zeta_0, K_\nu)$ . Take all other welding correspondences as before. Condition (2) is then satisfied by the new system of welding correspondences  $\{\alpha_\mu: \mu = 1, \dots, n\} \cup \{\alpha\}$ , so if (2) is sufficient for the existence of a local weld then  $X^\alpha$  formed relative to  $\{\alpha_\mu: \mu = 1, \dots, n\}$  and  $\tilde{X}^\alpha$  formed relative to  $\{\alpha_\mu: \mu = 1, \dots, n\} \cup \{\alpha\}$  are  $H$ -isomorphic in an open neighborhood of  $\chi(0)$ . This is a direct result of the choice of  $\alpha$ .

Consequently, the sufficiency of (1) for the existence of a local weld is proved once we have proved the following proposition.

Let the wedges  $D_\mu(K_\mu)$ ,  $\mu = 1, \dots, n$  be such that  $\eta_\mu = \zeta_{\mu+1}$  and denote  $\ell(\zeta_\mu, K_\mu)$  by  $\ell_\mu(K_\mu)$ . Let  $\alpha_\mu: \ell_\mu(K_\mu) \rightarrow \ell_\mu(K_{\mu+1})$  be a homeomorphism such that  $\alpha_\mu(0) = 0$ .

(1.2) PROPOSITION. Let  $\overline{X} = \cup \overline{D_\mu(K_\mu)}$  with welding correspondences  $\alpha_\mu$  as above which are  $C_0^{1+a}$  on  $\ell_\mu(K_\mu)$ . Then  $\overline{X}$  can be welded locally if

1° there exists  $p$  and  $q$ ,  $1 \leq p < q \leq n$  such that  $\zeta_p = \zeta_q + \pi$ ;

2°  $(d/dt) \alpha'_\mu(0) = 1$  for every  $\mu = 1, \dots, n$ .

Note that assumption 1° requires that  $n \geq 2$ .

The procedure for proving this proposition will be to weld each of the chains

$\{\bar{D}_p(K_p), \dots, \bar{D}_{q-1}(K_{q-1})\}$  and  $\{\bar{D}_q(K_q), \dots, \bar{D}_n(K_n), \dots, \bar{D}_{p-1}(K_{p-1})\}$  so that the results are half discs, and then to weld these two half discs. The chains are welded by welding two wedges at a time, which in turn can be reduced to welding two half discs. Thus the proof of proposition (1.2) for  $n > 2$  reduces essentially to the proof for  $n = 2$ . This special case will follow from known results about quasiconformal mapping.

For  $n = 2$  we may take  $\bar{D}_1(K_1)$  (resp.  $\bar{D}_2(K_2)$ ) to be the upper (resp. lower) half disc of  $G(K_1)$  (resp.  $G(K_2)$ ). The maps  $\alpha_1$  and  $\alpha_2^{-1}$  together define a  $C_0^{1+a}$  map  $\alpha$  from  $\text{bdy}_{\mathbb{C}^+} \bar{D}_1(K_1)$  onto  $\text{bdy}_{\mathbb{C}^-} \bar{D}_2(K_2)$  for which  $(d/dt) \alpha'(0) = 1$ . For ease of notation we will suppress the constants  $K_v$  in the notation  $\bar{D}_v(K_v)$ .

The procedure for finding  $A_1$  and  $A_2$  satisfying  $2^\circ$  above is due to C. BLANC ([2]; also see [4]). The map

$$P(x, y) = \alpha(x) + i(\alpha(x + y) - \alpha(x)), \quad w = x + iy$$

is defined and is a  $C_0^{1+a}$  homeomorphism on  $V \cap \bar{D}_1$  for some open neighborhood  $V$  of the origin. Since  $\alpha$  is a  $C_0^{1+a}$  map,  $P(x, y)$  is a quasiconformal map ([8]).  $P(x, y)$  satisfies  $P(x, 0) = \alpha(x)$  and  $P^{-1}(x, y) = \alpha^{-1}(x) + i(\alpha^{-1}(x + y) - \alpha^{-1}(x))$ .  $P^{-1}(x, y)$  is also quasiconformal and satisfies the usual Beltrami equation for

$$\mu(x, y) = (-1 + i) \left[ \frac{d\alpha^{-1}}{dt}(x + y) - \frac{d\alpha^{-1}}{dt}(x) \right] \cdot \left[ \frac{d\alpha^{-1}}{dt}(x + y) + \frac{d\alpha^{-1}}{dt}(x) + i \left\{ \frac{d\alpha^{-1}}{dt}(x + y) - \frac{d\alpha^{-1}}{dt}(x) \right\} \right]^{-1}.$$

Define

$$\mu^*(x, y) = \begin{cases} \mu(x, y), & \begin{cases} \in V^* \cap D_1 \\ \notin V^* \cap D_1; \end{cases} \end{cases} \quad (3)$$

clearly  $\mu^*(x, y)$  is well-defined for some open neighborhood  $V^*$  of 0, and is a  $C^a$  function on  $V^*$ . It is known ([1]) that there is then a  $C^{1+a}$  homeomorphism  $A$  on an open neighborhood  $V'$  of 0 satisfying the Beltrami equation

$$A_{\bar{w}} = \mu^* A_w;$$

now  $A \circ P$  and  $A$  are 1-quasiconformal homeomorphisms on  $U \cap D_1$  and  $U \cap D_2$  respectively and therefore biholomorphic maps, where  $U = V \cap V' \cap V^*$ . Moreover,  $\mathcal{C} = A|_{\text{bdy}_{\mathbb{C}^-} \bar{D}_2}$  is a  $C^{1+a}$  simple curve and  $A^{-1} \circ (A \circ P)|_{\text{bdy}_{\mathbb{C}^+} \bar{D}_1} = \alpha$ . The uniqueness of the weld follows from [4], theorem 1 and so proposition (1.2) is proved for  $n = 2$ .

It should be noted that  $(d/dt) \alpha(0) = 1$  has not been used, but rather only the fact that  $(d/dt) \alpha_1(0) = (d/dt) \alpha_2^{-1}(0) \neq 0$  so that  $\alpha_1$  and  $\alpha_2^{-1}$  together define a  $C_0^{1+a}$  map  $\alpha$ . Therefore proposition (1.2) for  $n = 2$  will provide for a general  $H$ -manifold  $X$  the

local weld at points on  $\bar{X}_\beta$  which are not vertices of the given simplicial structure on  $\bar{X}_\beta$ . What  $(d/dt)\alpha(0)=1$  does mean is that for any two biholomorphic  $A_1$  and  $A_2$  defining the local weld in (1.2) for  $n=2$ ,

$$\frac{d}{dw} A_1(0) = \frac{d}{dw} A_2(0).$$

This is the basic fact which allows us to weld piece by piece when  $n > 2$ .

In order to prove (1.2) for  $n > 2$ , we first weld the wedges  $\bar{D}_p(K_p)$  and  $\bar{D}_{p+1}(K_{p+1})$  and then prepare the result for welding to  $\bar{D}_{p+2}(K_{p+2})$ . Extend  $\bar{D}_p(K_p)$  and  $\bar{D}_{p+1}(K_{p+1})$  to half discs with bounding line segments  $\ell'_p(K_p) (= \{t \cdot \exp(i\zeta_p) : -K'_p \leq t \leq K'_p\})$  and  $\ell'_{p+1}(K_{p+1})$  respectively, and extend  $\alpha_p$  to a  $C^{1+a}$  homeomorphism  $\alpha_p$  of  $\ell'_p(K_p)$  onto  $\ell'_{p+1}(K_{p+1})$ . There is an open neighborhood  $U_p$  of  $\chi(0)$  in  $X^\alpha$  for which the two half discs have properties (a) and (b) on  $\chi^{-1}(U_p)$  for the welding correspondence  $\alpha_p$ . Let  $A'_{p+1}$  and  $A'_p$  denote the biholomorphic welding maps, the domains of  $A'_p$  and  $A'_{p+1}$  being subsets of the half discs containing  $\bar{D}_p(K_p)$  and  $\bar{D}_{p+1}(K_{p+1})$  respectively. The curve  $A_{p+1} | l_{p+1}(K_{p+1}) \cap \chi^{-1}(U_p)$  is  $C^{1+a}$ ; this follows from Kellogg's theorem. Extend this curve from  $A'_{p+1}(0)$  through the image set  $A_p(\chi^{-1}(U_p)) \cup A'_{p+1}(\chi^{-1}(U_p))$  to its boundary in a simple,  $C^{1+a}$  way so that it does not intersect  $A'_p(\bar{D}_p(K_p) \cap \chi^{-1}(U_p)) \cup A'_{p+1}(\bar{D}_{p+1}(K_{p+1}) \cap \chi^{-1}(U_p))$  except at  $A'_{p+1}(0) = A'_p(0)$ . Let  $R_p$  be the region in  $\mathbb{C}$  bounded by this extended curve and the boundary of the image set and containing  $A'_p(\chi^{-1}(U_p)) \cup A'_{p+1}(\chi^{-1}(U_p))$ . Map this region by biholomorphic  $f_p$  onto a bounded half disc whose bounding line segment is a finite segment of  $\ell'_{p+1}(\infty)$ , which does not intersect  $D_{p+2}(K_{p+2})$ , and such that  $f_p \circ A'_p(0) = f_p \circ A'_{p+1}(0) = 0$  while the image of the above extended curve is on  $\ell'_{p+1}(\infty)$  (a slightly smaller  $U_p$  may have to be chosen for this last part). Let  $B_p = f_p \circ A'_p$ ,  $B_{p+1} = f_p \circ A'_{p+1}$ ; since  $(d/dw) A'_p(0) = (d/dw) A'_{p+1}(0)$ ,  $f_p$  may also be normalized by the condition

$$\left| \frac{d}{dw} B_p(0) \right| = \left| \frac{d}{dw} B_{p+1}(0) \right| = 1.$$

Now weld  $B_p(\bar{D}_p(K_p) \cap \chi^{-1}(U_p)) \cup B_{p+1}(\bar{D}_{p+1}(K_{p+1}) \cap \chi^{-1}(U_p))$  to  $\bar{D}_{p+2}(K_{p+2})$  in exactly the same way for the welding correspondence  $\alpha_{p+1} \circ B_{p+1}^{-1}$ . Denote the resulting welding maps by  $B'_{p+1}$  and  $B_{p+2}$ , the domains of  $B'_{p+1}$  and  $B_{p+2}$  containing  $B_{p+1}(\bar{D}_{p+1}(K_{p+1}) \cap \chi^{-1}(U_{p+1}))$  and  $D_{p+2}(K_{p+2}) \cap \chi^{-1}(U_{p+1})$  respectively, where  $U_{p+1} \subseteq U_p$  is also an open neighborhood of  $\chi(0)$  in  $X^\alpha$ . Continue this process until in an open neighborhood  $U_{q-2}$  of  $\chi(0)$  in  $X^\alpha$  the wedges  $\bar{D}_p(K_p) \cap \chi^{-1}(U_{q-2})$  through  $\bar{D}_{q-2}(K_{q-2}) \cap \chi^{-1}(U_{q-2})$  have been welded together, and then determine the neighborhood  $U_{q-1} \subseteq U_{q-2}$  and the welding maps  $A'_{q-2}$  and  $A'_{q-1}$  of the next weld. Because of condition 1° of the proposition and the fact that all maps so far determined are angle-preserving at the origin, the  $C^{1+a}$  extension of the curve  $A'_{q-1} | \ell_{q-1}(K_{q-1}) \cap$

$\cap \chi^{-1}(U_{q-1})$  will be taken to be  $A''_{q-2} \circ B'_{q-3} \circ \cdots \circ B'_{p+1} \circ B_p \mid \ell_{p-1}(K_{p-1}) \cap \chi^{-1}(U_{q-1})$ . Determine the map  $f_{q-1}$  as before with its proper normalization. The final result of welding the chain  $\{\bar{D}_p(K_p), \dots, \bar{D}_{q-1}(K_{q-1})\}$  is then a half-disc  $\bar{\mathcal{D}}_1(K'_{q-1})$  with bounding line segment  $\ell'_{q-1}(K'_{q-1}) = \ell'_{q-1}(K'_{q-1})$  for some positive number  $K'_{q-1}$ .

Now weld the chain  $\{\bar{D}_q(K_q), \dots, \bar{D}_n(K_n), \dots, \bar{D}_{p-1}(K_{p-1})\}$  in exactly the same way, starting with  $\bar{D}_q(K_q)$  and  $\bar{D}_{q+1}(K_{q+1})$ . Use analogous notation throughout, i.e. the notation for the mappings, constants, etc. is determined by substituting  $q$  for  $p$  in the previous ones. Again, the result is a half disc  $\bar{\mathcal{D}}_2(K'_{p-1})$  with bounding line segment  $\ell'_{p-1}(K'_{p-1}) = \ell'_{q-1}(K'_{p-1})$  for some positive number  $K'_{p-1}$ .

The final step is to weld these two half discs with the welding correspondence  $\alpha: \ell'_{p-1}(K'_{q-1}) \rightarrow \ell'_{p-1}(K'_{p-1})$  given by

$$\beta = \alpha \mid \ell_{p-1}(K'_{q-1}) = B_{p-1} \circ \alpha_{p-1}^{-1} \circ B_p^{-1} \circ B_{p+1}^{-1} \circ \cdots \circ B_{q-2}^{-1},$$

while

$$\gamma = \alpha \mid \ell_{q-1}(K'_{q-1}) = B'_{p-2} \circ \cdots \circ B'_q \circ \alpha_{q-1} \circ B_{q-1}^{-1}.$$

Clearly both  $\beta$  and  $\gamma$  are  $C_0^{1+a}$  maps on their respective domains. Moreover, by condition 2° of the proposition and the chosen normalization of the maps  $f$ , one has  $(d/dt) \beta'(0) = (d/dt) \gamma'(0) = 1$ . Therefore  $\alpha$  is a  $C_0^{1+a}$  map. Weld the half discs,  $V$  being the open neighborhood of  $\chi(0)$  in  $X^\alpha$  for this local weld and  $\Gamma_1, \Gamma_2$  being the welding maps, where the domains of  $\Gamma_1$  and  $\Gamma_2$  are  $\bar{\mathcal{D}}_1(K'_{q-1}) \cap \chi^{-1}(V)$  and  $\bar{\mathcal{D}}_2(K'_{p-1}) \cap \chi^{-1}(V)$  respectively.

The welding maps  $A_\mu, \mu=1, \dots, n$  of 2°) are then given by

$$\begin{aligned} A_p &= \Gamma_1 \circ B'_{q-2} \circ \cdots \circ B'_{p+1} \circ B_p \mid \bar{D}_p(K_p) \cap \chi^{-1}(V) \\ A_{p+1} &= \Gamma_1 \circ B'_{q-2} \circ \cdots \circ B'_{p+1} \circ B_{p+1} \mid \bar{D}_{p+1}(K_{p+1}) \cap \chi^{-1}(V) \\ &\vdots \\ A_{q-2} &= \Gamma_1 \circ B'_{q-2} \circ B_{q-2} \mid \bar{D}_{q-2}(K_{q-2}) \cap \chi^{-1}(V) \\ A_{q-1} &= \Gamma_1 \circ B_{q-1} \mid \bar{D}_{q-1}(K_{q-1}) \cap \chi^{-1}(V); \end{aligned}$$

The  $A_q$  through  $A_{p-1}$  are given by replacing  $\Gamma_1$  with  $\Gamma_2$  and interchanging  $p$  and  $q$  in the above formulas. Each  $A_\mu$  is biholomorphic on the interior of its domain; a straightforward computation shows that the equations 2°) (ii) are satisfied. That each curve  $\mathcal{C}_\mu = A_\mu \mid \ell_\mu(K_\mu) \cap \chi^{-1}(V)$  is  $C^{1+a}$  follows from the constructions in the proof and repeated applications of Kellogg's theorem. The uniqueness of the weld follows in a straightforward way from the uniqueness in the case  $n=2$ , and so the proof of proposition (1.2) is complete.

*Remark.* It has been shown that the general local welding problem is solved by reducing it to the situation of proposition (1.2). If the original welding correspondences are  $C_0^{1+a}$  maps, the reduced ones are  $C_0^{1+a'}$  for some  $a' \leq a$ , and as seen from the proof of (1.2),  $S^\alpha$  will be a star of  $C^{1+a'}$  curves in a neighborhood of  $\chi(0)$ . It is easy

to show that  $a'$  may be given by

$$a' = a \cdot \min(1, (2\pi\zeta)^{-1}).$$

In fact, in terms of a given  $a$ , this is the maximum value of  $a'$  which will work.

## § 2. The General Case

The global welding problem is essentially done, since the problems of existence and uniqueness of the weld and whether or not  $S^a$  is a  $C^{1+a'}$  1-complex on  $X^a$  are local ones.<sup>4)</sup> The only question remaining is the form of the condition (1) on the welding correspondences at vertices  $x$  of the simplicial structure on  $\bar{X}_\beta$  for which either  $\text{pr } x$  is of order 1 in  $S$  or  $\chi(x)$  has order 1 in  $S^a$ . The easiest way to give the condition in these cases is to allow "generalized" wedges as coordinate neighborhoods at vertices of  $\bar{X}_\beta$  and in the local welding problem of § 1. A generalized wedge is a space  $\bar{G}$  formed from a disc  $G$  in  $\mathbb{C}$  with center 0 and a ray  $T$  originating at 0 and passing through  $\partial G$ ;  $\text{Int } \bar{G}$  is holomorphically isomorphic to  $G \setminus T$ . Everything can be done as before as long as one is careful on the boundary of the generalized discs. The welding condition is essentially the same as (1) whenever  $x$  is such that  $\text{pr } x$  has order 1 and  $\chi(x)$  has order  $> 1$ . If  $\chi(x)$  has order 1, or equivalently if  $\alpha_x(x) = x$ , let  $\alpha'_x = \bar{\varphi} \circ \alpha_x \circ \bar{\varphi}^{-1}$ ,  $\bar{\varphi}$  a coordinate at  $x$  in  $\bar{X}$ . Then  $(d/dt) \alpha''_x(x)$  is independent of the choice of  $\bar{\varphi}$ , and in this case the welding condition is

$$\frac{d}{dt} \alpha''_x(x) = 1. \quad (1)$$

Summing up, we have

(2.1) THEOREM. *Let  $X$  be an  $H$ -manifold and  $S \subseteq X$  a  $C^{1+a}$  1-complex on  $X$ . Let  $\{\sigma^1, \alpha_\lambda: \lambda \in \Lambda\}$  be defined as above and form  $X^a$ . Then  $X^a$  can be given a unique  $H$ -structure so that*

- (i)  $\chi \circ \text{pr}^{-1}: X \setminus S \rightarrow X^a \setminus S^a$  is an  $H$ -isomorphism;
  - (ii)  $S^a$  is a  $C^{1+a'}$  1-complex on  $X^a$  for some  $a' \leq a$ ,
- if and only if for every vertex  $x$  of the simplicial structure on  $\bar{X}_\beta$ ,

$$\prod \{\dot{\alpha}_y(y): \chi(y) = \chi(x)\} = 1.$$

*Remark.* If in the welding problem  $S$  is a  $C^{n+a}$  1-complex ( $n > 1$ ), one may ask for conditions under which  $S^a$  would be a  $C^{n+a'}$  1-complex for some  $a' \leq a$ . The technique used here does not provide such conditions because the function  $\mu^*(x, y)$

<sup>4)</sup> The Hölder index  $a'$  is locally determined. It can happen that no global Hölder constant on  $S^a$  exists.

defined in formula (3) is only of class  $C^a$  no matter how smooth the welding correspondence  $\alpha$  is.

The application of theorem (2.1) to transmission problems with shifts requires that both  $X$  and  $X^\alpha$  be Riemann surfaces, i.e. orientable  $H$ -manifolds. If  $X$  is a Riemann surface and  $X^\alpha$  an  $H$ -manifold, it is useful to describe the orientability of  $X^\alpha$  in terms of so-called welding signatures on  $\bar{X}_\beta$ .

Let  $x \in \bar{X}_j$ ,  $\text{pr}_j := \text{pr} \mid \bar{X}_j$ , and  $\varphi$  a coordinate at  $\text{pr} \bar{x}$ ;  $\varphi \circ \text{pr}_j$  is then a coordinate at  $x$ . If  $x \in \bar{X}_\beta$ , let  $f$  be a biholomorphic map of  $\varphi \circ \text{pr}_j(U)$  onto a wedge with tip at the origin,  $f$  being angle-preserving on  $\bar{X} \cap U$  and  $U$  a sufficiently small coordinate neighborhood of  $x$ . This describes the  $H$ -structure on  $\bar{X}$  as in the introduction, and in fact gives  $\bar{X}$  the structure of a bordered Riemann surface. Denote the wedge at  $x \in \bar{X}_\beta$  by  $D_x$ , and suppose that  $x$  is a vertex of the simplicial structure on  $\bar{X}_\beta$ . Consider the set  $\{D_y : \chi(y) = \chi(x)\}$ . In order to put this set of wedges in the correct position for the local weld in § 1, some of them must be "turned over", i.e. mapped onto themselves by what is essentially the complex conjugation map  $\gamma : \mathbb{C} \rightarrow \mathbb{C}$ ,  $\gamma(w) = \bar{w}$ . There is of course no unique way of determining which wedges will or will not be mapped by  $\gamma$ , but for each such choice one has welding signatures  $\tilde{\sigma}(x)$ , where  $\tilde{\sigma}(x) = 1$  if  $D_x$  is mapped by  $\gamma$  and  $\tilde{\sigma}(x) = 0$  otherwise. If  $x \in \bar{X}_\beta$  is not a vertex, say  $x \in \text{Int} \sigma_\lambda^1$ , an orientation on  $X$  induces by way of  $\text{pr}$  orientations on  $\sigma_\lambda^1$  and  $\sigma_{\varphi(\lambda)}^1$ . If  $\alpha_\lambda$  reverses these orientations, define  $\tilde{\sigma}(x)$  and  $\tilde{\sigma}(\alpha_\lambda(x))$  to both have value 0 or both have value 1, while if  $\alpha_\lambda$  preserves orientation, define one to have value 0 and the other 1.

(2.2) THEOREM. *If  $X$  is a Riemann surface and  $X^\alpha$  an  $H$ -manifold, obtained from  $X$  by welding, then  $\bar{X}^\alpha$  can be given the structure of a Riemann surface if and only if welding signatures on  $\bar{X}_\beta$  may be chosen so as to have constant value  $\tilde{\sigma}(j)$  on each  $\bar{X}_\beta \cap \bar{X}_j$ , in which case the complex structure on  $X^\alpha$  can be chosen so that  $\chi_j := \chi \mid \text{Int} \bar{X}_j$  is biholomorphic if  $\tilde{\sigma}(j) = 0$  and biantiholomorphic if  $\tilde{\sigma}(j) = 1$ .*

*Proof.* Obvious.

Another topological property of the welded  $H$ -manifold  $X^\alpha$  is the following

(2.3) THEOREM.  *$X^\alpha$  is compact if and only if  $X$  is compact.*

### § 3. Welding Holomorphic Families of Riemann Surfaces

Let  $\omega : \mathfrak{B} \rightarrow M$  be a holomorphic mapping of the complex manifold  $\mathfrak{B}$  onto the complex manifold  $M$ .  $\omega$  is called a *holomorphic family of Riemann surfaces* if for every  $v \in \mathfrak{B}$  there is an open neighborhood  $U$  of  $v$  in  $\mathfrak{B}$  and a biholomorphic map  $\psi_U$  of  $U$  onto  $G \times \omega(U)$  such that if  $\text{pr}_2$  denotes the projection  $(w, x) \rightarrow x$ , then  $\omega = \text{pr}_2 \circ \psi_U$ ;  $G$  is the unit disc  $|w| < 1$  in  $\mathbb{C}$ . Let  $S$  be a closed subset of  $\mathfrak{B}$  which is *locally a star of  $C^{1+a(x)}$  curves depending holomorphically on  $x \in M$*  ([6]). Define a simplicial structure on  $S$  so that

- (i) the restriction to each surface in the family is a simplicial structure as before;
- (ii) the set of simplices of codimension 2 is a complex submanifold of  $\mathfrak{B}$ .

$S$  together with such a structure is called a  $C^{1+a(x)}$  complex on  $\mathfrak{B}$  of codimension 1 depending holomorphically on  $x \in M$ . Let  $\{\sigma_\lambda^1: \lambda \in \Lambda\}$  be the simplices of codimension 1 and  $\varphi: \Lambda \rightarrow \Lambda$  as before. The welding correspondences  $\alpha_\lambda: \sigma_\lambda^1 \rightarrow \sigma_{\varphi(\lambda)}^1$  are  $C^{1+a(x)}$  maps depending holomorphically on  $x \in M$  ([6]) satisfying

$$\omega \circ \text{pr} \circ \alpha_\lambda(v) = \omega \circ \text{pr}(v)$$

for all  $v \in \sigma_\lambda^1$ , where  $\text{pr}$  is the projection map  $\bar{\mathfrak{B}} \rightarrow \mathfrak{B}$ .

The local welding situation for holomorphic families of Riemann surfaces is essentially as follows. Let  $P$  be a polycylinder in  $\mathbb{C}^n$ ,  $I = \{t: 0 \leq t < 1\}$ , and  $I' = \{t: -1 < t < 1\}$ . In  $D \times P$  we are given the family of curves  $S(\mathcal{C}_v(t, z)) = (a(z) + b_v(z)t, z)$ , where  $(t, z) \in I \times P$ ,  $a, b_v: P \rightarrow \mathbb{C}$  are holomorphic and the  $b_v$  are nowhere zero, and for every pair  $1 \leq v, \mu \leq n$  with  $v \neq \mu$ ,  $b_v(z) \neq b_\mu(z)$  for all  $z \in P$ . The welding correspondences  $\alpha_v$  are homeomorphisms of  $S(\mathcal{C}_v)$  onto itself such that

1°  $\alpha_v | \mathcal{C}_v(I \times \{z\}) \times \{z\}$  is a  $C_0^{1+a(z)}$  map of  $\mathcal{C}_v(I \times \{z\}) \times \{z\}$  onto itself for every  $z \in P$ ;

2°  $\alpha_v | S(\mathcal{C}_v(\{t\} \times P))$  is holomorphic for every  $t \in I$ .

The results of § 1 carry over to this situation with only minor adjustments in the proofs. For example, consider the case  $n=2$  and  $\arg b_1(z) = \arg b_2(z) + \pi$  for all  $z \in P$ . For each  $z \in P$  define the affine transformation  $\mathcal{L}_z(w) = a(z) + b_1(z)w$ , and let  $\mathcal{L}: \mathbb{C} \times P \rightarrow \mathbb{C}$  be the holomorphic map  $\mathcal{L}(w, z) = \mathcal{L}_z(w)$ . Define the map  $\beta$  of  $I' \times P$  onto itself by

$$\beta(t, z) = \begin{cases} (\mathcal{L}_z^{-1} \text{pr}_1 \circ \alpha_1(\mathcal{L}(t, z), z), z), & t \geq 0 \\ (\mathcal{L}_z^{-1} \text{pr}_1 \circ \alpha_2^{-1}(\mathcal{L}(t, z), z), z), & t < 0. \end{cases}$$

Clearly there is  $\beta'$  such that

$$\beta(t, z) = (\beta'(t, z), z);$$

since  $\beta'$  is real-valued and holomorphic in  $z$  it is constant in  $z$ , i.e. there is a  $C_0^{1+a}$  map  $\gamma: I' \rightarrow I'$  so that  $\gamma(t) = \beta'(t, z)$ . Then if  $A'_1$  and  $A'_2$  are the local welding maps for  $\gamma$  determined in § 1, clearly  $A_v(w, z) = (\mathcal{L}(A'_v(w), z), z)$  ( $v=1, 2$ ) are local welding maps for this special parameterized case.

The global welding problem for a holomorphic family of Riemann surfaces  $\omega: \mathfrak{B} \rightarrow M$  and a  $C^{1+a(z)}$  complex  $S$  of codimension 1 depending holomorphically on  $x \in M$  requires more than simple adjustments in the proofs, however. In order to use the results of the local welding problem as it is presented above, one must as in § 2 be able to map coordinate neighborhoods of points  $v \in \bar{\mathfrak{B}}_\beta$  biholomorphically onto “holomorphic families of wedges”. If  $\dim M = 0$ , which is the situation of § 2, this can always be done. But when  $\dim M > 0$  there are restrictions.



Let  $\mathcal{C}:\partial G \times P \rightarrow \mathbb{C}$  be a family of simple closed  $C^{1+a(z)}$  curves depending holomorphically on  $z \in P$  and denote by  $\Omega_z$  the bounded region in  $\mathbb{C}$  for which  $\partial\Omega_z = \mathcal{C}(\partial G \times \{z\})$ . There is no loss in generality in assuming that for some  $z^\circ \in P$ ,  $\mathcal{C} \mid \partial G \times \{z^\circ\}$  is the boundary value of a biholomorphic map of  $G$  onto  $\Omega_{z^\circ}$ .

(3.1) PROPOSITION. *Let  $\mathcal{C}:\partial G \times P \rightarrow \mathbb{C}$  be as above. In order that there exist a map  $f:G \times P \rightarrow \mathbb{C}$  satisfying*

(i)  *$f$  is holomorphic;*

(ii)  *$f \mid G \times \{z\}$  is a biholomorphic map of  $G$  onto  $\Omega_z$  for every  $z \in P$ ,*

*it is both necessary and sufficient that  $\mathcal{C}$  be the boundary value of a map  $\mathcal{C}:G \times P \rightarrow \mathbb{C}$  satisfying (i) and (ii).*

*Proof.* ([5]).

By an *analytic complex* on  $\mathfrak{B}$  of codimension 1 depending holomorphically on  $x \in M$  we mean a  $C^{1+a(x)}$  complex  $S$  as above for which every  $v \in \bar{\mathfrak{B}}_\beta$  has a coordinate neighborhood in  $\bar{\mathfrak{B}}$  biholomorphically equivalent to a holomorphic family of wedges. In view of proposition (3.1) this means that  $S$  must be locally a star of analytic curves depending holomorphically on  $x \in M$  and satisfy further conditions at the simplices of codimension 2 in the minimal simplicial structure on  $S$ .

If  $\mathfrak{B}^\alpha$  is a complex manifold obtained by welding and  $S^\alpha$  is a  $C^{1+a'(x)}$  complex of codimension 1 depending holomorphically on  $x \in M$ , then  $\omega^\alpha:\mathfrak{B}^\alpha \setminus S^\alpha \rightarrow M$  is a holomorphic family of Riemann surfaces, where

$$\omega^\alpha(v^\alpha) = \omega(\text{pr} \circ \chi^{-1}(v^\alpha)),$$

and since  $\omega \circ \text{pr} \circ \alpha_\lambda(v) = \omega \circ \text{pr}(v)$  for all  $v \in \sigma_\lambda^1$  and all  $\lambda \in \Lambda$ ,  $\omega^\alpha$  has a unique holomorphic extension to  $\omega^\alpha:\mathfrak{B}^\alpha \rightarrow M$  which is also a holomorphic family of Riemann surfaces.

One remark about notation. Let  $\alpha''(t, z)$  be defined analogously to  $\alpha''(t)$  in the introduction for a point  $v \in \bar{\mathfrak{B}}_\beta$ . Then  $\dot{\alpha}_v(v)$  will now denote  $(\partial/\partial t) \alpha''(0, z)$  where  $(0, z)$  is the coordinate of  $v$ .

(3.2) THEOREM. *Let  $\omega:\mathfrak{B} \rightarrow M$  be a holomorphic family of Riemann surfaces,  $S$  an analytic complex on  $\mathfrak{B} \rightarrow M$  of codimension 1 depending holomorphically on  $x \in M$ , and  $\{\alpha_\lambda:\lambda \in \Lambda\}$  a set of  $C_0^{1+a(x)}$  welding correspondences depending holomorphically on  $x \in M$ . Suppose that there are welding signatures  $\{\tilde{\sigma}(\bar{v}):\bar{v} \in \bar{\mathfrak{B}}_\beta\}$  satisfying  $\tilde{\sigma}(\bar{v})=0$  for all  $\bar{v} \in \bar{\mathfrak{B}}_\beta$ . Then*

1°  $\omega^\alpha:\mathfrak{B}^\alpha \rightarrow M$  *is a holomorphic family of Riemann surfaces obtained uniquely from  $\omega:\mathfrak{B} \rightarrow M$ , hence*

$$\chi \circ \text{pr}^{-1}:\mathfrak{B} \setminus S \rightarrow \mathfrak{B}^\alpha \setminus S^\alpha$$

*is biholomorphic; and*

2°  $S^\alpha$  *is a  $C^{1+a'(x)}$  complex of codimension 1 depending holomorphically on  $x \in M$  for some  $a'(x) \leq a(x)$*



if and only if at every point  $v$  in some simplex of codimension 2 of the given simplicial structure on  $\bar{\mathfrak{B}}_\beta$ ,

$$\prod \{\dot{\alpha}_v(y) : \chi(y) = \chi(v)\} = 1.$$

*Remark.* Suppose that  $S$  is a family of simple, closed  $C^{1+a(x)}$  curves depending holomorphically on  $x \in M$  and denote the welding correspondences by  $\alpha_1$  and  $\alpha_2$ .  $\alpha'_v = \text{pr} \circ \alpha_v \circ (\text{pr} \mid \sigma_v^1)^{-1}$  is a map of  $S$  onto itself ( $v=1, 2$ ) such that  $\alpha'_1 = \alpha'_2{}^{-1}$ ; if  $\alpha'_1$  is the boundary value of a biholomorphic map  $\alpha'_1 : U \rightarrow \mathfrak{B}$  for some open neighborhood  $U$  of  $\sigma_1^1$  in  $\bar{\mathfrak{B}}$ , then the conclusions of theorem (3.2) hold. In general, the analyticity condition on the complex  $S$  in theorem (3.2) can be replaced by analyticity conditions on the welding correspondences. Moreover, the analyticity condition on  $S$  implies that each  $\text{pr} \sigma_\lambda^1$  is a pseudoconvex hypersurface in  $\mathfrak{B}$ , but nowhere strongly pseudoconvex. On the other hand, one has

(3.3) THEOREM. *If  $\text{pr} \sigma_\lambda^1$  is a strongly pseudoconvex hypersurface on  $\mathfrak{B}$  and the conclusions of theorem (3.2) are true, then  $\text{pr} \circ \alpha_{\lambda'} \circ (\text{pr} \mid \sigma_\lambda^1)^{-1}$  is the boundary value of a biholomorphic map  $\text{pr} U_\lambda \rightarrow \mathfrak{B}$  for some open neighborhood  $U_\lambda$  of either  $\text{Int} \sigma_\lambda^1$  or  $\text{Int} \sigma_{\lambda'}^1$  on  $\bar{\mathfrak{B}}$ , where  $\lambda'$  is that unique index satisfying  $\lambda' \neq \lambda$  and  $\text{pr} \sigma_{\lambda'}^1 = \text{pr} \sigma_\lambda^1$ .*

II. Let  $X$  be a Riemann surface,  $S$  a  $C^{1+a}$  1-complex on  $X$  and  $\{\sigma_\lambda^1, \alpha_\lambda : \lambda \in \Lambda\}$  welding data as in chapter I. satisfying the condition (1). Suppose that there are welding signatures  $\{\tilde{\sigma}(\bar{x}) : \bar{x} \in \bar{X}_\beta\}$  which have constant value  $\tilde{\sigma}(j)$  on each connected component  $\bar{X}_j$  of  $\bar{X}$ .  $X^\alpha$  is then a Riemann surface. Form  $(\bar{X}^\alpha)$  relative to  $X^\alpha$  and  $S^\alpha$  with the projection  $\text{pr}^\alpha : (\bar{X}^\alpha) \rightarrow X^\alpha$  and denote it by  $\bar{X}^\alpha$ . Both  $\bar{X}$  and  $\bar{X}^\alpha$  are bordered Riemann surfaces for which  $\text{pr} : \text{Int} \bar{X} \rightarrow X$  and  $\text{pr}^\alpha : \text{Int} \bar{X}^\alpha \rightarrow X^\alpha$  are holomorphic maps. Clearly there is a homeomorphism  $A : \bar{X} \rightarrow \bar{X}^\alpha$  such that  $\text{pr}^\alpha \circ A = \chi$ ; both  $A$  and  $A^{-1}$  are  $C^{1+a}$  maps. According to (2.2), the complex structure on  $X^\alpha$ , and thereby on  $\bar{X}^\alpha$ , can be chose so that  $A \mid \text{Int} \bar{X}_j$  is either biholomorphic or biantiholomorphic according to whether  $\tilde{\sigma}(j)=0$  or 1.

Let  $\beta : \bar{X}_\beta \rightarrow \bar{X}_\beta$  and  $\beta^\alpha : \bar{X}_\beta^\alpha \rightarrow \bar{X}_\beta^\alpha$  be the successor maps defined in [6] and define  $\beta_\lambda = A^{-1} \circ \beta^\alpha \circ A$ ,  $\beta_\lambda : \bar{X}_\beta \rightarrow \bar{X}_\beta$ . For every  $\bar{x} \in \bar{X}_j \cap \bar{X}_\beta$ , define  $j' = \beta_\lambda(j, \bar{x})$  to be that index for which  $\beta_\lambda(\bar{x}) \in \bar{X}_{j'}$ . A coherent set of signatures  $\sum_\alpha = \{\sigma_{x^\alpha} : x^\alpha \in S^\alpha\}$  on the  $C^{1+a}$  1-complex  $S^\alpha$  ([6]) induces in the obvious way a set of signatures  $\{\sigma(\bar{x}^\alpha) : \bar{x}^\alpha \in \bar{X}_\beta^\alpha\}$  on  $\bar{X}_\beta^\alpha$ . Define the signatures  $\{\sigma_\alpha(\bar{x}) : \bar{x} \in \bar{X}_\beta\}$  on  $\bar{X}_\beta$  by the rule  $\sigma_\alpha(\bar{x}) = \sigma(A(\bar{x}))$ .

Let  $L$  be a complex Lie group and  $f : \bar{X}_\beta \rightarrow L$  a Hölder continuous map.  $f$  is said to be *compatible with the welding data* if for every  $\lambda \in \Lambda$  and every  $\bar{x} \in \sigma_\lambda^1$   $f(\bar{x}) = f(\alpha_\lambda(\bar{x}))$ ; if so,  $f$  induces the Hölder continuous map  $f^\alpha : S^\alpha \rightarrow L$  by the rule  $f(\bar{x}) = f^\alpha(\chi(\bar{x}))$ .  $f$  is said to be *compatible with  $\sum_\alpha$*  if  $f^\alpha(x^\alpha)^{|\sigma_{x^\alpha}|} \equiv e$  on  $S^\alpha$ ,  $e$  being the unit of  $L$ .

#### § 4. The Haseman Problem

Given

1) a Riemann surface  $X$ , a  $C^{1+a}$  1-complex  $S$  on  $X$ , welding data  $\{\sigma_\lambda^1, \alpha_\lambda: \lambda \in A\}$  as in chapter I satisfying condition (1) and corresponding welding signatures  $\{\sigma(\bar{x}): \bar{x} \in \bar{X}\}$ , and a coherent set of signatures  $\sum_\alpha$  on  $S^\alpha$ ;

2) a complex Lie group  $L$  which acts as a complex automorphism group on the complex space  $F$ , where  $F$  has an antiholomorphic involution  $\iota$ ;

3) a Hölder continuous map  $f: \bar{X}_\beta \rightarrow L$  which is compatible with both  $\sum_\alpha$  and the welding data,

the Haseman problem is to find holomorphic maps  $s_j: \text{Int } \bar{X}_j \rightarrow F$  for each  $j$  such that

a)  $s_j$  has a continuous extension to  $\bar{X}_j$ ;

b) for every  $\lambda \in A$  and every  $x \in \sigma_\lambda^1$ ,

$$\tilde{\iota}^{\tilde{\sigma}(\alpha_\lambda(x))} \circ s_{\beta_\lambda(j, x)}(\alpha_\lambda(x)) = f(x)^{\sigma_\alpha(x)} \tilde{\iota}^{\sigma(x)} \circ s_j(x). \quad (4)$$

(4.1) THEOREM. *If the welding signatures have constant value  $\tilde{\sigma}(j)$  on each  $\bar{X}_j$  there is then a holomorphic fibre bundle  $\hat{\mathfrak{F}} \rightarrow X^\alpha$  over the welded Riemann surface  $X^\alpha$  with structure group  $L$  and fibre  $F$  and an isomorphism from the space of global holomorphic sections in  $\hat{\mathfrak{F}}$  onto the space of solutions of the above Haseman problem. This isomorphism is functorial in the obvious sense.*

*Proof.* Let  $s_j^\alpha = \tilde{\iota}^{\tilde{\sigma}(j)} \circ s_j \circ A^{-1}$  for every  $j$ .  $s_j^\alpha: \bar{X}_j^\alpha \rightarrow F$  is continuous,  $s_j^\alpha|_{\text{Int } \bar{X}_j^\alpha}$  is holomorphic, and for every  $x^\alpha \in \bar{X}_\beta^\alpha$

$$s_{\beta_\alpha(j, x^\alpha)}^\alpha(\beta^\alpha x^\alpha) = f^\alpha(\text{pr}^\alpha x^\alpha)^{\sigma(x^\alpha)} s_j^\alpha(x^\alpha). \quad (5)$$

Clearly there is an isomorphism from the space of solutions of the Haseman problem (4) onto the space of solutions of the Riemann-Privalov problem (5). The theorem now follows from the results in [6].

When  $L$  is the general linear group  $GL(q, \mathbb{C})$  and  $F = \mathbb{C}^q$  another form of the Haseman problem can be solved. Given

1) a Riemann surface  $X$ , a simple closed  $C^{1+a}$  curve  $S$  on  $X$  together with a  $C_0^{1+a}$  homeomorphism  $\alpha'$  of  $S$  onto itself.  $\alpha'$  induces the  $C_0^{1+a}$  homeomorphism  $\alpha: \bar{X}_2 \cap \bar{X}_\beta \rightarrow \bar{X}_1 \cap \bar{X}_\beta$  in the obvious way ( $\bar{X}_1$  and  $\bar{X}_2$  are the two connected components of  $\bar{X}$ ) for which there are welding signatures  $\tilde{\sigma}(1)$  and  $\tilde{\sigma}(2)$ ;

2) the involution  $\iota: \mathbb{C}^q \rightarrow \mathbb{C}^q$  is the map  $\gamma$  which sends each entry of  $z \in \mathbb{C}^q$  into its complex conjugate;

3) a continuous map  $f_2: S \rightarrow GL(q, \mathbb{C})$ , Hölder continuous  $g_2: S \rightarrow GL(q, \mathbb{C})$  and  $q \times q$  matrices of functions  $f_1, f_3, g_1, g_3$  for which  $\gamma^{\tilde{\sigma}(1)} \circ f_1, \gamma^{\tilde{\sigma}(1)} \circ f_3, \gamma^{\tilde{\sigma}(2)} \circ g_1, \gamma^{\tilde{\sigma}(2)} \circ g_3$  are meromorphic matrices in an open neighborhood  $U$  of  $S$  whose determinants are not identically zero,

the problem is to find holomorphic maps  $s_j: \text{Int } \bar{X}_j \rightarrow \mathbb{C}^q$  which have angular boundary values almost everywhere on  $\bar{X}_j \cap \bar{X}_\beta$  (i.e., boundary values taken along nontangential paths to  $\bar{X}_j \cap \bar{X}_\beta$ ) and satisfy for almost all  $\bar{x} \in \bar{X}_2 \cap \bar{X}_\beta$  the equation

$$(f_1 f_2 f_3) (\text{pr } \alpha(\bar{x})) \gamma^{\sigma(1)} \circ s_1(\alpha(\bar{x})) = (g_1 g_2 g_3) (\text{pr } \bar{x}) \gamma^{\tilde{\sigma}(2)} \circ s_2(\bar{x}). \quad (6)$$

As before, we will associate with (6) a holomorphic cocycle with values in  $\text{GL}(q, \mathbb{C})$  on the welded Riemann surface  $X^\alpha$  by considering an associated problem on  $X^\alpha$  of the Riemann-Privalov type. In order to avoid inconvenient notation this associated problem will also be given on  $X$ . Given

- 1)  $X, S, \alpha, \tilde{\sigma}(1), \tilde{\sigma}(2)$  as above;
  - 2)  $\iota = \gamma$  as above;
  - 3)  $f_2, g_2$  as above and  $f_v, g_v$  ( $v=1, 3$ ) are  $q \times q$  matrices of functions satisfying
    - i) there is an open neighborhood  $U$  of  $S$  such that  $f_v$  (resp.  $g_v$ ) is a meromorphic matrix on  $\text{pr } \bar{X}_1 \cap U \setminus S$  (resp.  $\text{pr } \bar{X}_2 \cap U \setminus S$ ) whose determinant is not identically zero;
    - ii)  $\gamma^{\tilde{\sigma}(1)} \circ f_v \circ \text{pr} \circ \chi_1^{-1}$  and  $\gamma^{\tilde{\sigma}(2)} \circ g_v \circ \text{pr} \circ \chi_2^{-1}$  extend to meromorphic matrices in an open neighborhood of  $S^\alpha$ ,
- the problem is to find  $s_1, s_2$  as above so that for almost all  $\bar{x} \in \bar{X}_2 \cap \bar{X}_\beta$

$$(f_1 f_2 f_3) (\text{pr } \bar{x}) \cdot s_1(\beta \bar{x}) = (g_1 g_2 g_3) (\text{pr } \bar{x}) \cdot s_2(\bar{x}). \quad (7)$$

Since  $S$  is a simple closed  $C^{1+a}$  curve there is an open neighborhood  $V$  of  $S$  which is schlichtartig, and so by the Koebe mapping theorem there is a biholomorphic map  $v$  of  $V$  into a domain in the 1 dimensional projective space  $\mathbb{P}^1$ . Clearly this can be done so that  $v(S)$  does not contain the point at infinity. Moreover,  $v(S)$  is a simple closed  $C^{1+a}$  curve in  $\mathbb{P}^1$ . Let  $G'_j$  be a continuous map of  $v(V \cap \text{pr } \bar{X}_j)$  into  $\text{GL}(q, \mathbb{C})$  ( $j=1, 2$ ) whose restriction to  $\text{Int } v(V \cap \text{pr } \bar{X}_j)$  is holomorphic and such that for all  $t \in v(S)$ ,  $G'_1(t) = g_2(v^{-1}(t)) \cdot G'_2(t)$ . The existence of such maps is known ([6] or [11], § 127). Since  $G'_1(t)^{-1} f_2(v^{-1}(t)) G'_1(t)$  is continuous, it is known ([10], [12]) that there are holomorphic maps  $\bar{X}'_j: \text{Int } v(V \cap \text{pr } \bar{X}_j) \rightarrow \text{GL}(q, \mathbb{C})$  with angular boundary values almost everywhere on  $v(S)$  which are in  $L_p(S)$  for every  $p > 1$  and satisfy almost everywhere on  $v(S)$  the equation  $X'_2(t) = G'_1(t)^{-1} \cdot f_2(v^{-1}(t)) \cdot G'_1(t) X'_1(t)$ . Let  $G_j = G'_j \circ v$ ,  $X'_j = X'_j \circ v$ .

Two cases must be considered. Either (1)  $\alpha$  is the boundary value of a biholomorphic map  $\alpha: \text{Int } \text{pr } \bar{X}_2 \cap V$  or (2) it is not. In the first case  $f_1$  extends to a meromorphic matrix in an open neighborhood of  $S$ . Let  $V' \subseteq V$  be an open neighborhood of  $S$  so that on  $V' \setminus S$   $f_1, f_3, g_1$ , and  $g_3$  are holomorphic matrices with values in  $\text{GL}(q, \mathbb{C})$ . Define  $Y_2 = f_1 \cdot X'_2$  if  $\alpha$  is as in (1) and  $Y_2 = X'_2$  otherwise. Let  $Y_1 = f_3^{-1} \cdot X'_1$ ,  $F_1 = G_1$  and  $F_2 = g_3^{-1} \cdot G_2$ , and let  $\text{Int } \text{pr } \bar{X}_j = U_j$ ,  $V' = U_3$ . Then  $g_{13} = F_1 \cdot Y_1$ ,  $g_{23} = F_2 \cdot Y_2$  is a holomorphic  $U = \{U_v: v=1, 2, 3\}$ -cocycle with values in  $\text{GL}(q, \mathbb{C})$  and defines the holomorphic vectorbundle  $\bar{W} \rightarrow X$ .

(4.2) THEOREM. Suppose that  $g_1 = 1$  and

(1) if  $\alpha$  is the boundary value of a biholomorphic map  $\alpha: \text{Int pr } \bar{X}_2 \cap V \rightarrow X$  for some open neighborhood  $V$  of  $S$ , then  $f_v G_1 = G_1 f_v$  ( $v = 1, 3$ );

(2) if  $\alpha$  is not as in (1), then  $f_1 = 1$  and  $f_3 G_1 = G_1 f_3$ .

Then there is an injection from the space of global holomorphic (resp. meromorphic) sections in  $\hat{W}$  to the space of holomorphic (resp. meromorphic) solutions of problem (7). If  $f_1, f_3$  and  $g_3$  have values in  $\text{GL}(q, \mathbb{C})$  and it is required that the boundary values of a solution  $\{s_1, s_2\}$  of (7) satisfy

$$s_j \circ \chi_j^{-1} \circ v^{-1} \mid v(S) \in L_p(v(S))$$

for all  $p > 1$  and  $j = 1, 2$ , this map is bijective.

*Proof.* The proof is the same as that of theorem (4.1) in [6], using known properties of  $X'_1$  and  $X'_2$ .

Suppose now that  $f_2$  is Hölder continuous. It may then be required that the solutions  $s_1, s_2$  satisfy

(A<sub>1</sub>)  $s_1$  and  $s_2$  have continuous extensions to  $\bar{X}_1$  and  $\bar{X}_2$  respectively.

We will also require the following property.

(A<sub>2</sub>) Let  $\{x_1, \dots, x_k\}$  be the smallest set of points on  $S$  (in the sense of inclusion) such that  $f_1, f_3$  and  $g_3$  have values in  $\text{GL}(q, \mathbb{C})$  on  $S \setminus \{x_1, \dots, x_k\}$ . Then  $f_1(\text{pr } \bar{x}) f_2(x_\mu)$ ,  $f_3(\text{pr } \bar{x}) s_1(\bar{x})$  and  $g_1(\text{pr } \bar{x}) g_2(x_\mu) g_3(\text{pr } \bar{x}) s_2(\bar{x})$  should have continuous extensions to  $\bar{X}_1 \cap \text{pr}^{-1}(U_\mu)$  and  $\bar{X}_2 \cap \text{pr}^{-1}(U_\mu)$  respectively for an open neighborhood  $U_\mu$  of  $x_\mu$ ,  $\mu = 1, \dots, k$ .

Just as in theorem (4.2), the correspondence between the space of global holomorphic sections in  $\hat{W}$  and the space of holomorphic solutions of problem (7) is not in general surjective. For example, let  $X = \mathbb{P}^1$ ,  $S = \{w: |w| = 1\}$ ,  $\alpha = \text{identity}$ ,  $q = 1$ ,  $f_1 = g_1 = f_2 = g_2 = 1$  and  $f_3 = g_3 = (w - 1)^{-1}$ . Then  $s_1 = s_2 = 1$  is a solution of (7), but  $s_1, s_2, s_3 = (w - 1)^{-1}$  is a meromorphic, not a holomorphic, section in  $\hat{W}$ . However, unlike theorem (4.2) the correspondence is also not in general injective. To see this, take all data as in the above example except for  $f_3$  and  $g_3$  and set  $f_3 = w - 1$ ,  $g_3 = 1$ . Then  $\{s_1 = (w - 1)^{-1}, s_2 = s_3 = 1\}$  is a holomorphic section in  $\hat{W}$ , but  $\{s_1, s_2\}$  is not a solution of (7) in the above sense because it does not satisfy (A<sub>1</sub>). This situation is rectified by adjusting the cocycle which defines  $\hat{W}$ .

Let  $n_{\mu, q}$  be the integers such that for any meromorphic section  $\{s_1, s_2, s_3\}$  in  $\hat{W}$ , the  $q$ th component of  $s_3$  has a singularity of order  $\geq n_{\mu, q}$  at  $x_\mu$  for every  $q = 1, \dots, q$  if and only if  $s_1$  and  $s_2$  have continuous extensions to  $\bar{X}_1 \cap \text{pr}^{-1} U_\mu$  and  $\bar{X}_2 \cap \text{pr}^{-1} U_\mu$  respectively for some open neighborhood  $U_\mu$  of  $x_\mu$ . The  $n_{\mu, q}$  are easily computed in terms of the orders of the singularities of the components of  $\gamma^{\tilde{\sigma}(1)} \circ f_v \circ \text{pr} \circ \chi_1^{-1}$  and  $\gamma^{\tilde{\sigma}(2)} \circ g_3 \circ \text{pr} \circ \chi_2^{-1}$ ,  $v = 1, 3$ . Let  $h_q$  be a meromorphic function on  $U_3$  with divisor

$\sum_{\mu=1}^k n_{\mu, q} x_{\mu}$ ,  $h = h_1 \oplus \dots \oplus h_q$  and  $\tilde{g}_{13} = g_{13}h$ ,  $\tilde{g}_{23} = g_{23}h$ . The cocycle  $\tilde{g}_{ij}$  defines the holomorphic vectorbundle  $\tilde{W} \rightarrow X$ .

(4.3) COROLLARY. Suppose that in problem (7)  $f_v$  and  $g_v$  ( $v=1, 3$ ) satisfy the hypothesis of (4.2) and furthermore that  $f_2$  is Hölder continuous. Then there is an isomorphism from the space of global holomorphic (resp. meromorphic) sections in the vectorbundle  $\tilde{W} \rightarrow X$  onto the space of holomorphic (resp. meromorphic) solutions of problem (7) which satisfy the conditions  $(A_1)$  and  $(A_2)$  above.

### § 5. The Carleman Problem

Given

1) a bordered Riemann surface  $X$  whose boundary is a  $C^{1+a}$  1-complex with simplicial structure  $\{\sigma_{\lambda} : \lambda \in \Lambda\}$ ;

2) a homeomorphism  $\alpha : bdy X \rightarrow bdy X$  which preserves this simplicial structure and for which  $\alpha_{\lambda} = \alpha|_{\text{Int} \sigma_{\lambda}^1}$  is a  $C_0^{1+a}$  map for every  $\lambda \in \Lambda$  and satisfies the *Carleman condition*  $\alpha \circ \alpha = \text{identity}$ . If  $\alpha_{\lambda}$  is orientation preserving (resp. reversing) we write  $\alpha_{\lambda} = \alpha_{\lambda}^+$  (resp.  $\alpha_{\lambda} = \alpha_{\lambda}^-$ );

3) a complex Lie group  $L$  with antiholomorphic involution  $\iota : L \rightarrow L$  which acts as a complex automorphism group on the abelian complex Lie group  $L_1$ , which also has an antiholomorphic involution  $\iota_1 : L_1 \rightarrow L_1$ , such that  $\iota$  and  $\iota_1$  are automorphisms satisfying

$$\iota_1(\ell \cdot \ell_1) = \iota(\ell) \cdot \iota_1(\ell_1) \quad \text{for all } \ell \in L, \ell_1 \in L_1;$$

4) a Hölder continuous map  $f : bdy X \rightarrow L$  satisfying the *Carleman condition*

$$\begin{aligned} (+) \quad f(x) &= \iota_1 \circ f(\alpha(x))^{-1} \quad \text{for all } x \in \sigma_{\lambda}^1 \quad \text{if } \alpha_{\lambda} = \alpha_{\lambda}^+ \\ (-) \quad f(x) &= f(\alpha(x))^{-1} \quad \text{for all } x \in \sigma_{\lambda}^1 \quad \text{if } \alpha_{\lambda} = \alpha_{\lambda}^-, \end{aligned}$$

the Carleman problem is to find a holomorphic map  $s : \text{Int} X \rightarrow L_1$  which has a continuous extension to  $X$  and satisfies

$$\begin{aligned} s(\alpha(x)) &= f(x) \iota_1 \circ s(x) \quad \text{for all } x \in \sigma_{\lambda}^1 \quad \text{if } \alpha_{\lambda} = \alpha_{\lambda}^+ \\ s(\alpha(x)) &= f(x) s(x) \quad \text{for all } x \in \sigma_{\lambda}^1 \quad \text{if } \alpha_{\lambda} = \alpha_{\lambda}^-, \end{aligned} \quad (8)$$

$\lambda \in \Lambda$ .

Let  $X_1 = X$ ,  $X_2 = X$  as sets but with opposite structures and  $\bar{X}$  equal the disjoint union  $X_1 \cup X_2$ . The simplicial structure  $\{\sigma_{\lambda}^1 : \lambda \in \Lambda\}$  on  $bdy X_1$  defines a similar structure on  $bdy X_2$  in the obvious way and thereby one on  $\bar{X}_{\beta} = bdy X_1 \cup bdy X_2$  which will be denoted by  $\{\sigma_{\rho}^1 : \rho \in P\}$ . There is a natural involution  $\gamma$  of  $\bar{X}$  onto itself which maps  $X_1$  onto  $X_2$  and  $X_2$  onto  $X_1$ , is antiholomorphic on  $\bar{X} \setminus \bar{X}_{\beta}$ , and continuous on  $\bar{X}$ . Define the bijections  $\varphi : \Lambda \rightarrow \Lambda$  by  $\alpha(\sigma_{\lambda}^1) = \sigma_{\varphi(\lambda)}^1$  and  $\psi : P \rightarrow P$  by

1. if there exists  $\lambda \in \Lambda$  for which  $\sigma_{\lambda}^1 = \sigma_{\rho}^1$ , then  $\gamma \circ \alpha(\sigma_{\lambda}^1) = \sigma_{\psi(\rho)}^1$ ;

2. if there exists  $\lambda \in \Lambda$  for which  $\sigma_\lambda^1 = \gamma(\sigma_\rho^1)$ , then  $\alpha^{-1} \circ \gamma(\sigma_\rho^1) = \sigma_{\psi(\rho)}^1$ .

Correspondingly, for each  $\rho \in P$  define the  $C_0^{1+a}$  homeomorphism  $\alpha_\rho: \sigma_\rho^1 \rightarrow \sigma_{\psi(\rho)}^1$  by the rules

- 1'. if there exists  $\lambda \in \Lambda$  for which  $\sigma_\lambda^1 = \sigma_\rho^1$ , then  $\alpha_\rho = \gamma \circ \alpha_\lambda$ ;  
 2'. if there exists  $\lambda \in \Lambda$  for which  $\sigma_\lambda^1 = \gamma(\sigma_\rho^1)$ , then  $\alpha_\rho = \alpha_\lambda^{-1} \circ \gamma$ .

Define the Hölder continuous map  $\tilde{f}: \bar{X}_\beta \rightarrow L$  as follows:

- 1°. if for  $\sigma_\rho^1$  there is  $\sigma_\lambda^1 = \sigma_\rho^1$ , then

$$\tilde{f}(\bar{x}) = \begin{cases} \iota \circ f(\bar{x}) & \text{for all } \bar{x} \in \sigma_\rho^1 \text{ if } \alpha_\lambda = \alpha_\lambda^+ \\ f(\bar{x}) & \text{for all } \bar{x} \in \sigma_\rho^1 \text{ if } \alpha_\lambda = \alpha_\lambda^-; \end{cases}$$

- 2°. if for  $\sigma_\rho^1$  there is  $\sigma_\lambda^1 = \iota(\sigma_\rho^1)$ , then

$$\tilde{f}(\bar{x}) = \begin{cases} \iota \circ f(\alpha_\rho(\bar{x})) & \text{for all } \bar{x} \in \sigma_\rho^1 \text{ if } \alpha_\lambda = \alpha_\lambda^+ \\ f(\alpha_\rho(\bar{x})) & \text{for all } \bar{x} \in \sigma_\rho^1 \text{ if } \alpha_\lambda = \alpha_\lambda^-; \end{cases}$$

Define the signatures  $\{\sigma(\bar{x}): \bar{x} \in \bar{X}_\beta\}$  by the rule

$$\sigma(\bar{x}) = \begin{cases} 1, & \bar{x} \in b \, dy \, X_1 \\ -1, & \bar{x} \in b \, dy \, X_2 \end{cases}$$

and the welding signatures  $\{\tilde{\sigma}(\bar{x}): \bar{x} \in \bar{X}_\beta\}$  by

$$\tilde{\sigma}(\bar{x}) = \begin{cases} 0, & \bar{x} \in b \, dy \, X_1 \text{ or } \bar{x} \in b \, dy \, X_2 \cap \sigma_\rho^1 \text{ and } \alpha_\rho = \alpha_\rho^+ \\ 1, & \bar{x} \in b \, dy \, X_2 \cap \sigma_\rho^1 \text{ and } \alpha_\rho = \alpha_\rho^-; \end{cases}$$

$\tilde{\sigma}(x)$  is well-defined since it is constant on each connected component of  $\bar{X}_\beta$ .

Finally, let  $\beta(1)=2$  and  $\beta(2)=1$  and consider the Haseman problem to find holomorphic maps  $s_v: \text{Int } X_v \rightarrow L_1$  with continuous extensions to  $X_v$  ( $v=1, 2$ ) such that for every  $x \in \bar{X}_\beta$

$$\iota_1^{\tilde{\sigma}(\alpha_\rho(x))} \circ s_{\beta(v)}(\alpha_\rho(x)) = \tilde{f}(x)^{\sigma(x)} \iota_1^{\sigma(x)} \circ s_v(x), \quad \text{where } x \in \sigma_\rho^1. \quad (9)$$

(5.1) THEOREM. Suppose that  $\alpha$  is such that either  $\alpha_\lambda = \alpha_\lambda^+$  for all  $\lambda \in \Lambda$  or  $\alpha_\lambda = \alpha_\lambda^-$  for all  $\lambda \in \Lambda$ . Then every solution  $s$  of the Carleman problem (8) defines a solution of the Haseman problem (9), namely  $\{s_1 = s, s_2 = \iota_1 \circ s \circ \gamma\}$ . On the other hand, if  $\{s_1, s_2\}$  is a solution of (9), then  $s = s_1 + \iota_1 \circ s_2 \circ \gamma$  is a solution of (8).

*Proof.* Verification.

Let  $\mathcal{L}_1$  (resp.  $\mathcal{L}_2$ ) be the space of solutions of problem (8) (resp. (9)) and  $\chi_1: \mathcal{L}_1 \rightarrow \mathcal{L}_2$ ,  $\chi_2: \mathcal{L}_2 \rightarrow \mathcal{L}_1$  the maps described in (5.1).  $\chi_1$  is an injection.  $\chi_2$  is not bijective, and so there is in general nothing equivalent to (4.1) for the Carleman problem. However, the existence of global holomorphic sections in the fibre bundle  $\hat{\mathfrak{F}} \rightarrow X^\alpha$  described by problem (9) implies the existence of solutions of the Carleman problem (8).

If  $L_1 = \mathbf{C}^q$  and  $L$  is a complex Lie subgroup of the complex affine group  $GA(q, \mathbf{C})$ , it makes sense to define  $\chi_2$  by the rule  $\{s_1, s_2\} \rightarrow \frac{1}{2}(s_1 + \iota_1 \circ s_2 \circ \gamma)$ . Theorem (5.1) remains valid and moreover,  $\chi_2 \circ \chi_1 = \text{identity}$ . If  $\hat{W} \rightarrow X^\alpha$  is the holomorphic vector-bundle associated with the holomorphic affine bundle  $\hat{\mathcal{F}} \rightarrow X^\alpha$  which corresponds to the homogeneous Carleman problem (see [6]) and  $\mathcal{O}(\hat{W})$  is the sheaf of germs of holomorphic sections in  $\hat{W}$ , then from (5.1) and [6], theorem (5.1) one has

(5.2) THEOREM.  $\mathcal{L}_1$  is either empty or  $\dim_{\mathbf{R}} \mathcal{L}_1 = \dim_{\mathbf{C}} H^0(X^\alpha, \mathcal{O}(\hat{W}))$ .

*Remarks.* 1. It is clear that one can study Carleman problems corresponding to the various forms of problem (6) discussed in § 4. Moreover, because of the results in § 3 and [6], the Haseman and Carleman problems can also be analysed when given on a holomorphic family of Riemann surfaces with appropriate  $S$ , welding data (i.e., shifts) and transmission map  $f$ .

2. As in [6], known properties of the space of global holomorphic sections in a global holomorphic fibre bundle can be used to describe the solution spaces of the various problems discussed here. The results in [6] carry over to the Haseman and Carleman problems when modified in the obvious ways to take into account the fact that the correspondences in the various theorems of § 4 and § 5 are not necessarily bijective.

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