LOCAL EXISTENCE FOR THE CAUCHY PROBLEM OF A REACTION-DIFFUSION ETC(U)

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LOCAL EXISTENCE FOR THE CAUCHY PROBLEM
OF A REACTION-DIFFUSION SYSTEM WITH
DISCONTINUOUS NONLINEARITY

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Local existence for the Cauchy problem of a reaction-diffusion system with discontinuous nonlinearity

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Abstract

The pure initial value problem for the system of equations

\[ \begin{align*}
    v_t &= v_{xx} + f(v) - w \\
    w_t &= \varepsilon(v - \gamma w)
\end{align*} \]

is considered. Here \( \varepsilon \) and \( \gamma \) are positive constants, and \( f(v) = v - H(v - a) \) where \( H \) is the Heaviside step function and \( a \in (0, \frac{1}{2}) \). Because of the discontinuity in \( f \) one cannot expect the solution of this system to be very smooth. Sufficient conditions on the initial data are given which guarantee the existence of a classical solution in \( \mathbb{R} \times (0, T) \) for some positive time \( T \).

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SIGNIFICANCE AND EXPLANATION

The most famous model for nerve conduction is due to Hodgkin and Huxley. However, a mathematical analysis of their model has proven very difficult. The complexity of the Hodgkin and Huxley model has led a number of other authors to introduce simpler models. In this report we consider one such simplification.

It has been demonstrated (experimentally) that impulses in the nerve axon travel with constant shape and velocity. Mathematically, this corresponds to traveling wave solutions. A number of authors have proven that the mathematical equations considered here do possess traveling wave solutions.

Another property of impulses in the nerve axon is the existence of a threshold phenomenon. This corresponds to the biological fact that a minimum stimulus is needed to trigger an impulse. Here we prove some preliminary results which will be used in a later report when it is demonstrated that the equations under study do indeed exhibit a threshold phenomenon.

The responsibility for the wording and views expressed in this descriptive summary lies with MRC, and not with the author of this report.
LOCAL EXISTENCE FOR THE CAUCHY PROBLEM OF A
REACTION-DIFFUSION SYSTEM WITH DISCONTINUOUS NONLINEARITY

David Terman

1. INTRODUCTION

In this paper we consider the pure initial value problem for the FitzHugh-Nagumo
equations

\begin{align*}
  v_t &= v_{xx} + f(v) - w, \\
  w_t &= \varepsilon(v - v_x),
\end{align*}

the initial data being \((v(x,0), w(x,0)) = (\psi(x), 0)\). Here \(\varepsilon\) and \(\gamma\) are positive
constants. These equations were introduced as a qualitative model for nerve conduction
[2,5,7]. We follow McKean [4] and assume that \(f(v)\) is given by

\[ f(v) = v - H(v - \alpha) \]

where \(H\) is the Heaviside step function and \(\alpha \in (0, \frac{1}{2})\).

Note that because \(f(v)\) is discontinuous we cannot expect the solution, \((v,w)\), to
be very smooth. By a classical solution of System (1.1) we mean the following:

Definition: Let \(S_T = \mathbb{R} \times (0,T)\) and \(G_T = \{(x,t) \in S_T : v(x,t) \neq \alpha\}.\) Then
\((v(x,t),w(x,t))\) is said to be a classical solution of the Cauchy problem (1.1) in \(S_T\) if:

(a) \((v,w)\) along with \((v_x,v_{xx})\) are bounded continuous functions in \(S_T,\)

(b) in \(G_T\), \(v_{xx}, v_t\) and \(w_t\) are continuous functions which satisfy the system
of Equations (1.1),

(c) \(\lim_{t \to 0} v(x,t) = \psi(x)\) and \(\lim_{t \to 0} w(x,t) = 0\) for each \(x \in \mathbb{R}.\)

Throughout this paper we assume that \(\psi(x) = v(x,0)\) satisfies the following
conditions:

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(a) \( \varphi(x) \in C^1(\mathbb{R}) \)
(b) \( \varphi(x) = \varphi(-x) \) in \( \mathbb{R} \)
(c) \( \varphi(x_0) = a \) for some \( x_0 > 0 \)
(d) \( \varphi(x) > a \) if and only if \( |x| < x_0 \)
(e) \( \varphi'(x_0) < 0 \)
(f) \( \varphi''(x) \) is a bounded continuous function except possibly at \( x = x_0 \).

This last condition is needed in order to obtain sufficient a priori bounds on the derivatives of the solution of System (1.1).

In this paper we prove that if \( \varphi(x) \) satisfies (1.2) then there exists a classical solution of the Cauchy problem (1.1) in \( S_T \) for some \( T > 0 \). Here we give an outline of the proof.

From Assumption (1.2) we expect there to exist a positive constant \( T \) and a smooth function \( s(t) \), defined in \([0,T]\), such that \( \varphi > a \) for \( |x| < s(t) \) and \( \varphi < a \) for \( |x| > s(t) \). Suppose that this is the case. We then set \( G = \{(x,t); |x| < s(t), 0 < t < T\} \) and let \( \chi_G \) be the characteristic step function of the region \( G \). It follows that if \( |x| < s(t) \), then \( (v,w) \) is a solution of the system of equations

\[
\begin{align*}
v_t &= v_{xx} - v + \chi_G - w \\
w_t &= \epsilon(v - \gamma w) \\
(v(x,0),w(x,0)) &= (\varphi(x),0)
\end{align*}
\]

in \( S_T \), in \( \mathbb{R} \).

Note that the first equation in (1.3) is similar to a nonhomogeneous heat equation while the second is just an ordinary differential equation. Formally, the solution of (1.3) can be written as:

\[
\begin{align*}
v(x,t) &= \int_0^s K(x-\xi,t)\varphi(\xi)d\xi + \int_0^t \int_0^{s(\tau)} K(x-\xi,t-\tau)\varphi(\xi)d\xi d\tau \\
&= -\int_0^t \int_0^{s(\tau)} K(x-\xi,t-\tau)w(\xi,\tau)d\xi d\tau \\
&= -\int_0^t \int_0^{\infty} \chi_G(x-\xi,t-\tau)w(\xi,\tau)d\xi d\tau \\
&= -\int_0^t \int_0^{\infty} \chi_G(x-\xi,t-\tau)w(\xi,\tau)d\xi d\tau \\
&= -\int_0^t \int_0^{\infty} \chi_G(x-\xi,t-\tau)w(\xi,\tau)d\xi d\tau \\
&= -\int_0^t \int_0^{\infty} \chi_G(x-\xi,t-\tau)w(\xi,\tau)d\xi d\tau
\end{align*}
\]

\[
w(x,t) = \epsilon e^{-\epsilon t} \int_0^\infty \chi_G(x-\xi)w(\xi,0)d\xi.
\]
Here \( K(x,t) = \frac{e^{-x^2/4t}}{2\pi^{1/2}t^{1/2}} \) is the fundamental solution of the linear differential equation

\[ (1.5) \quad \psi_t = \psi_{xx} - \psi. \]

Setting \( x = s(t) \) in (1.4) we find that, formally, \( s(t) \) must satisfy the integral equation

\[ (1.6) \quad s = \int_0^t K(s(t)-\xi,t)d\xi + \int_0^t \int_0^t K(s(t)-\xi,t-\tau)d\tau \]

Using an iteration procedure, we prove the existence of functions \( v(x,t), w(x,t), \) and \( s(t) \) which satisfy the Equations (1.4) and (1.6). We then show that \( (v,w) \) is the desired classical solution of the Cauchy problem (1.1) in \( S^+ \).

We now introduce some notation.

Let \( \psi(x,t) = \int_0^t K(x-\xi,t)d\xi \). Note that \( \psi(x,t) \) is the solution of the linear equation (1.5) with initial datum \( \psi(x,0) = \psi(x) \).

Suppose that \( a(t) \) is a positive, continuous function defined in \([0,T_1]\) for some \( T_1 > 0 \). Let \( z(x,t) \) be a continuous function defined in \( \mathbb{R} \times [0,T_1] \). Let

\[ \phi(z)(t) = \int_0^t K(a(t)-\xi,t-\tau)d\tau \] \text{ in } [0,T_1]

and

\[ \Gamma(z)(x,t) = \int_0^t K(x-\xi,t-\tau)z(\xi,\tau)d\tau \] \text{ in } \mathbb{R} \times [0,T_1].

Note that \( s(t) \) is a solution of (1.6) if and only if

\[ (1.7) \quad \psi(s(t),t) = a - \phi(s)(t) + \Gamma(w)(s(t),t). \]

In Section 2 we prove the properties of \( \psi \) and the operators \( \phi \) and \( \Gamma \) which are needed in the proof of the local existence of a classical solution of System (1.1). The proof of local existence is given in Section 3.
2. The Operators $\Phi$ and $\Gamma$

In this section we prove the properties of $\Phi$ and the operators $\Phi$ and $\Gamma$ which are needed in the proof of the local existence of a classical solution of System (1.1).

Lemma 2.1. $\Phi(x,t) \in C^m(\mathbb{R} \times \mathbb{R}^+).$ Furthermore, there exist positive constants $\delta_1, \delta_2, \delta_3$ and $\lambda$ such that $-\delta_1 < \Phi(x,t) < -\delta_2$ and $|\Phi_t(x,t)| < \delta_3$ in the rectangle $P = (x_0 - \lambda, x_0 + \lambda) \times (0,\lambda)$.

Proof: The first assertion is a standard result about solutions of Equation (1.5). The other assertions follow from the Assumptions (1.2, 26). (See Friedman [3], page 65) //

Lemma 2.2. Assume that $a(t) \in C^1(0,T).$ Then $\Phi(a)(t) \in C^1(0,T)$ and

$$\Phi(a)'(t) = \int_0^t K(a(t)-\xi,t)\,d\xi + \int_0^t (a(t)+a(\tau),t-\tau)[a'(\tau)+a'(t)]\,d\tau$$

(2.1)

Proof: Note that

$$\Phi(a)'(t) = \lim_{\epsilon \to 0} \frac{1}{\epsilon} \left[ (\Phi(a(t+\epsilon)) - \Phi(a(t)) \right]$$

$$= \lim_{\epsilon \to 0} \frac{1}{\epsilon} \left( \int_0^{\epsilon} \int_0^t K(a(t)-\xi,t-\tau)\,d\xi \right) - a'(t)$$

$$+ \int_0^t \int_{\xi}^t K(a(t)-\xi,t-\tau)\,d\xi - a(t)$$

$$= \lim_{\epsilon \to 0} \frac{1}{\epsilon} \left( \int_0^{\epsilon} \int_0^t K(a(t)-\xi,t-\tau)\,d\xi \right) - a'(t)$$

Passing to the limit we obtain (2.1). //
Lemma 2.3: Suppose that $\phi(t) \in C^1(0,T)$ and $|\phi(t)| \leq M$ in $(0,T)$. Then

$$|\phi'(t)| < 1 + 4MT^{1/2}$$

in $(0,T)$.

Proof: From (2.1) it follows that for $t \in (0,T)$,

$$|\phi'(t)| < 1 + 4M \int_0^t K(\phi(t) - \phi(\tau), t - \tau) d\tau$$

$$< 1 + 4MT\frac{1}{2}\int_0^t \frac{1}{2\pi (t-\tau)^{1/2}} d\tau$$

$$< 1 + 4MT^{1/2}.$$ //

Lemma 2.4: Let $\phi(t)$ be as in the previous Lemma. Suppose that for some $\rho \in (0,T)$ there exists a constant $M_1$ such that

$$|\phi'(t_2) - \phi'(t_1)| < M_1 |t_2 - t_1|^{1/2}$$

for each $t_0, t_1 \in (p,T)$. Then there exist positive constants $K_1$ and $K_2$, which depend only on $\rho$ and $M$, such that

$$|\phi'(t_1) - \phi'(t_0)| < (K_1 + K_2 M_1^{1/2}) |t_1 - t_0|^{1/2}$$

for each $t_0, t_1 \in (p,T)$.

Proof: Fix $t_0, t_1 \in (0,T)$. Then

$$\phi'(t_1) - \phi'(t_0) = \int_0^{t_1} \frac{d}{d\xi} \left( \int_0^\xi K(\phi(t_1) - \phi(\tau), t_1 - \tau) d\tau \right) dr + \int_0^{t_1} \frac{d}{d\xi} \left( \int_0^\xi K(\phi(t_1) + \phi(\tau), t_1 - \tau) d\tau \right) dr$$

$$- \int_0^{t_0} \frac{d}{d\xi} \left( \int_0^\xi K(\phi(t_0) - \phi(\tau), t_0 - \tau) d\tau \right) dr$$

$$+ \int_0^{t_1} \frac{d}{d\xi} \left( \int_0^\xi K(\phi(t_1) + \phi(\tau), t_1 - \tau) d\tau \right) dr$$

$$- \int_0^{t_0} \frac{d}{d\xi} \left( \int_0^\xi K(\phi(t_0) + \phi(\tau), t_0 - \tau) d\tau \right) dr$$

$$= [A] + [B] + [C].$$ -5-
Since $K(x,t)$ is an infinitely differentiable function of $(x,t)$ for $t > 0$, there exists a positive constant $D_1$ such that $|B_1| < D_1 |t_1 - t_0|^{1/2}$. Note that $D_1$ depends only on $p$ and $N$.

Next consider $[B]$ which we rewrite as

$$[B] = \int_{t_0}^{t_1} K(a(t_1) - a(t_0), t_0 - t)[a'(t_0) - a'(t_1)] \, dt$$

Note that,

$$a'(t_0) - a'(t_1) = [a'(t_0) - a'(t_0)] + [a'(t_0) - a'(t_1)]$$

$$< [a'(t_0) - a'(t_1)] + 2[M_1 |t_1 - t_0|^{1/2}].$$

Therefore,

$$[B] \leq \int_{t_0}^{t_1} K(a(t_1) - a(t_0), t_0 - t)[a'(t_0) - a'(t_1)] \, dt$$

$$+ \int_{t_0}^{t_1} [K(a(t_1) - a(t_0), t_0 - t) - K(a(t_0) - a(t_0), t_0 - t)] [a'(t_0) - a'(t_1)] \, dt$$

$$+ \int_{t_0}^{t_1} K(a(t_1) - a(t_0), t_0 - t) 2M_1 |t_1 - t_0|^{1/2} \, dt$$

$$= [B_1] + [B_2] + [B_3].$$

Now,

$$[B_1] < 2M \int_{t_0}^{t_1} \frac{1}{|t_1 - t_0|^{1/2}} \, dt$$

$$= \frac{2M}{\pi^{1/2}} \left| t_1^{1/2} - t_0^{1/2} \right|$$

$$< D_2 |t_1 - t_0|^{1/2}$$

for some constant $D_2$ which depends only on $M$ and $p$. We also have that
\[ |B_1| < 2M_1 |t_1-t_0|^{1/2} \int_0^{t_0} \frac{1}{2 \pi^{1/2} (t_0-\tau)^{1/2}} d\tau \]

\[ = 2M_1 |t_1-t_0|^{1/2} \int_0^{t_0} \frac{1}{2 \pi^{1/2} (t_0-\tau)^{1/2}} d\tau \]

Now consider \(|B_2|\). Note that

\[ |B_2| < 2M \int_0^{t_0} |\chi(a(t_1)-a(\tau+t_1-t_0),t_0-\tau) - \chi(a(t_0)-a(\tau),t_0-\tau)| d\tau \]

\[ = 2M \int_0^{t_0} \frac{1}{2 \pi^{1/2} (t_0-\tau)^{1/2}} |\gamma(t_1,\tau) - \gamma(t_0,\tau)| d\tau \]

where

\[ \gamma(t,\tau) = \frac{[a(t)-a(\tau+t-t_0)]^2}{4(t_0-\tau)} \]

Assume that \( t \in (0,t_0) \). Then, by the Mean Value Theorem,

\[ |\gamma(t_1,\tau) - \gamma(t_0,\tau)| < \frac{1}{t_1-t_0} |\gamma(n,\tau)| |t_1-t_0| \]

for some \( n \in (t_0,t_1) \). (We assume, without loss of generality, that \( t_0 < t_1 \).)

Note that

\[ \frac{1}{2 \pi^{1/2} (t_0-\tau)^{1/2}} \gamma(n,\tau) = \frac{2 |a(n)-a(\tau+n-t_0)|}{|t_0-\tau|} \frac{(a'(n) - a'(\tau+n-t_0))}{4(t_0-\tau)} \]

\[ \leq \frac{2M |t_1-t_0|}{|t_0-\tau|} \frac{1}{2M} < 1 \]

\[ = 4M^2 \]
Therefore,
\[ |(B_2)| < 8m^3 \int_0^{t_0} \frac{|t_1 - t_0|}{2s^{1/2}(t_0 - t)^{1/2}} \, dt \]
\[ < 8m^3 T^{1/2}|t_1 - t_0| \]
\[ < D_3|t_1 - t_0|^{1/2} \]
for some positive constant \( D_3 \) which depends only on \( M \). (Since we will eventually choose \( T \) to be small we assume throughout that \( T < 1 \).)

We have shown that
\[ |(B)| < |(B_1)| + |(B_2)| + |(B_3)| < D_4|t_1 - t_0|^{1/2} + 2mT^{1/2}|t_1 - t_0|^{1/2} \]
where \( D_4 = D_2 + D_3 \) depends only on \( M \) and \( \rho \).

A similar computation shows that there exist constants \( D_5 \) and \( D_6 \), which depends only on \( \rho \) and \( M \), such that
\[ |(c)| < D_5|t_1 - t_0|^{1/2} + D_6M^{1/2}|t_1 - t_0|^{1/2}. \]
In fact, this computation is much easier since \( K(a(t_1) + a(t), t_1 - t) \) and \( K(a(t_0) + a(t), t_0 - t) \) are smooth functions of \( t \).

Setting \( K_1 = D_1 + D_4 + D_6 \) and \( K_2 = 2 + D_6 \). The result follows. //

We now consider the operator \( \Gamma(z(t), t) \). In what follows we assume that \( T \) is some positive constant and \( S_T = R \times (0, T) \). We also assume that \( a(t), M, \rho \), and \( M_1 \) are as in the previous two lemmas, and set \( h(t) = \Gamma(z)(a(t), t) \).

**Lemma 2.5:** Assume that \( z(x, t) \in C^1([0, T]) \) with \( z(0, t) = z \). Then,

i) \( h(t) \in C^1([0, T]) \),

ii) there exist a constant \( K_3 \), which depends only on \( Z \), such that
\[ |h'(t)| < K_3 + 2m^{1/2} \] for \( t \in (0, T) \),

iii) there exist constants \( K_4 \) and \( K_5 \), which depend only on \( \rho, M, \) and \( Z \) such that
\[ |h'(t) - h'(t_0)| < (K_4 + K_5M^{1/2})|t_1 - t_0|^{1/2} \]
for each \( t_0, t_1 \in (0, T) \).

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Proof: Set \( g(x,t) = \Gamma(z)(x,t) \). Then \( g(x,t) \) is the solution of the inhomogeneous differential equation
\[
\frac{\partial g}{\partial t} = u_{xx} - u + z
\]
\( u(x,0) = 0 \).

Since \( z \in C^{1,1}(S_T) \) it follows from the Schauder estimates (see [3], page 65) that \( g \in C^{2,1/2}(S_T) \) where \( I \) depends only on \( Z \). We set \( K_6 = I \).

Furthermore, there exists a constant \( K_3 \), which depends only on \( Z \), such that
\[
|g_t(x,t)| < K_3 \text{ in } S_T.
\]
Note that in \( S_T \),
\[
|g(x,t)| = \int_0^T dt \int_0^t \int_X (x-\xi, t-\tau) z(\xi, \tau)d\xi
\]
\[
= \int_0^T dt \int_0^t \int_X (x-\xi, t-\tau) z(\xi, \tau)d\xi
\]
\[
= \int_0^T dt \int_0^t \int_X (x-\xi, t-\tau) z(\xi, \tau)d\xi
\]
\[
< Z\int_0^T dt \int_0^t \int_X (x-\xi, t-\tau) d\xi
\]
\[
< Z\int_0^T \frac{1}{(t-\tau)^{1/2}} d\tau
\]
\[
< Z^{-1/2}T^{1/2}.
\]

Now (i) follows because \( h(t) = g(t(a(t), t)) \) where \( g \) and \( a \) are both smooth functions. (ii) is true because
\[
(2.2) \quad h'(t) = g_x(a(t), t)a'(t) + g_t(a(t), t) \quad \text{in } (0, T)
\]
and, therefore,
\[
|h'(t)| < |Z|^{1/2} + K_3.
\]
Finally, it follows from (2.2) that for \( t_0, t_1 \in (p, T) \),

\[
|h'(t_1) - h'(t_0)| < \|q_{\alpha}(a(t_1), t_1) - q_{\alpha}(a(t_0), t_0)\|a'(t_1)|
\]

\[
+ \|q_{\epsilon}(a(t_0), t_0)\|a'(t_1) - a'(t_0)| + \|q_{\epsilon}(a(t_0), t_0) - q_{\epsilon}(a(t_1), t_1)\|
\]

\[
\leq K_6|t_1 - t_0|^{1/2} + 2e^{1/2}K_7|t_1 - t_0|^{1/2} + K_6|t_1 - t_0|^{1/2}.
\]

(iii) now follows if we set \( K_4 = K_6(N + 1) \) and \( K_5 = \mathbb{E} \). //
3. Local Existence

We are now ready to prove the existence of a classical solution of the Cauchy problem (1.1) in $S_T$ for some positive $T$. The idea of the proof is as follows.

Let $s_0(t) = x_0$ in $\mathbb{R}^d$ and suppose that for some time $T_1 > 0$ we have defined smooth functions $s_k(t)$ for $t \in [0, T_1)$, $k = 0, 1, \ldots, n$. We then let

$$(v_n(x,t), w_n(x,t))$$

be the solution of the integral equations

$$v_n(x,t) = \int_0^t K(x-x_\xi, t) \psi(\xi)d\xi + \int_0^t \int_0^t K(x-x_\xi, t_\tau) d\xi d\tau$$

$$w_n(x,t) = c e^{-\xi y t} \int_0^t e^{\xi y t} v_n(x, n)dn.$$ (3.1a)

That such a solution exists is proved in Lemma (3.1). We then use the Implicit Function Theorem to define $s_{n+1}(t)$ as the solution of the equation

$$\psi(s_{n+1}(t), t) = a - \psi(s_n(t)) + \Gamma(w_n)(s_n(t), t),$$

$$s_n(0) = x_0.$$ (3.1b)

We show that the sequences of functions $\{s_n(t)\}$, $\{v_n(x, t)\}$, and $\{w_n(x, t)\}$ converge to functions $s(t)$, $v(x, t)$, and $w(x, t)$. These functions are shown to be solutions of the Equations (1.4) and (1.6). It is then shown that $(v, w)$ is a classical solution of the Cauchy problem (1.1).

In what follows we let $s_0(t) = x_0$ in $\mathbb{R}^d$ and assume that smooth functions $s_k(t)$, $k = 0, 1, \ldots, n$, have been defined in $[0, T_1)$ for some $T_1 > 0$. Restrictions on $T_1$ will be given later. We assume that $M_k = \sup_{t \in (0, T_1)} |s'_k(t)| < \infty$, for $k = 0, 1, 2, \ldots, n$. For each $\rho \in (0, T_1)$ we assume that there exist constants $C_k$ such that

$$|s'_k(t_1) - s'_k(t_0)| \leq C_k |t_1 - t_0|^{1/2}$$

for each $k$ and $t_0, t_1 \in (0, T_1)$.

Lemma 3.1: There exist bounded, continuous functions $(v_n(x,t), w_n(x,t))$ which satisfy the Equations (3.1) in $S_T$. 

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Proof: The proof follows Evans and Shen [1]. Let \( v_{n_0}(x,t) = \psi(x) \) and \( w_{n_0}(x,t) = w(x,0) \neq 0 \) in \( S_{T_1} \). Assuming that \( v_{n_j}(x,t) \) and \( w_{n_j}(x,t) \) have been defined for \( j > 0 \), we let \( v_{n_{j+1}}(x,0) = \psi(x) \) and \( w_{n_{j+1}}(x,0) = w(x,0) \), and, for \( (x,t) \in S_{T_1} \),

\[

v_{n_{j+1}}(x,t) = \int_0^t K(x-\xi,t-\tau) \psi(\xi) d\xi + \int_0^t \int_0^\tau K(x-\xi,t-\tau) d\xi d\tau
\]

\[

w_{n_{j+1}}(x,t) = \int_0^t K(x-\xi,t-\tau) w(\xi,\tau) d\xi
\]

Equations (3.2).

The resulting sequences of functions, \( \{v_{n_j}(x,t)\} \) and \( \{w_{n_j}(x,t)\} \), are defined and continuous in \( S_{T_1} \). We show that these sequences converge uniformly to a solution of the Equations (3.1). Note that since \( \psi(x) \) is bounded, it follows from induction that each of the functions \( v_{n_j} \) and \( w_{n_j} \) are bounded.

Let

\[

\rho_j(t) = \sup_{(x,t) \in S_{T_1}} \left[ |v_{n_j}(x,t) - v_{n_{j-1}}(x,t)| + |w_{n_j}(x,t) - w_{n_{j-1}}(x,t)| \right].
\]

From Equations (3.2) it follows that, for \( (x,t) \in S_{T_1} \),

\[

|v_{n_{j+1}}(x,t) - v_{n_j}(x,t)| < \int_0^t \int_0^\tau K(x-\xi,t-\tau) |w_{n_j}(\xi,\tau) - w_{n_{j-1}}(\xi,\tau)| d\xi d\tau
\]

(3.3a)

\[

|w_{n_{j+1}}(x,t) - w_{n_j}(x,t)| < \epsilon \int_0^t |v_{n_j}(x,\tau) - v_{n_{j-1}}(x,\tau)| d\tau
\]

(3.3b)

Adding (3.3a) and (3.3b) we obtain

\[

\rho_{j+1}(t) < (1 + \epsilon) \int_0^t \rho_j(\tau) d\tau \quad \text{for} \quad t \in (0,T_1), \quad j = 1,2,\ldots.
\]

If \( K \) is a bound on \( \rho_j(t) \) for \( 0 < t < T_1 \) we have

\[

\rho_1(t) < K, \quad \rho_2(t) < (1 + \epsilon)K, \quad \ldots, \rho_{j+1}(t) < \frac{K((1+\epsilon)t)^j}{j!}, \quad \ldots.
\]

Thus, \( \sum_{j=1}^{\infty} \rho_j(t) < \frac{K((1+\epsilon)t)^{j+1}}{(j+1)!} < K_1 \) and the sequences \( \{v_{n_j}(x,t)\} \) and \( \{w_{n_j}(x,t)\} \) converge uniformly in \( S_{T_1} \) to limit functions \( v_n(x,t) \) and \( w_n(x,t) \).
Moreover, passing to the limit in Equations (3.2) we find that \( v_n(x,t) \) and \( w_n(x,t) \) satisfy the Equations (3.1) in \( S_{T_1} \).

From the proof of the preceding Lemma it follows that there exist constants \( V \) and \( W \) such that \( |v_n(x,t)| < V \) and \( |w_n(x,t)| < W \) in \( S_{T_1} \). Note that \( V \) and \( W \) can be chosen independent of the curve \( s_n(t) \). From (3.1) it follows that \( (v_n)_x(x,t) \) and \( (w_n)_x(x,t) \) both exist in \( S_{T_1} \), except possibly at \( |x| = s_n(t) \), \( 0 < t < T_1 \).

**Lemma 3.2.** There exist constants \( V_1 \) and \( W_1 \), independent of the curve \( s_n(t) \), such that \( |(v_n)_x(x,t)| < V_1 \) and \( |(w_n)_x(x,t)| < W_1 \) in \( S_{T_1} \), except possibly at \( |x| = s_n(t) \).

**Proof:** Suppose that \( x \neq s_n(t) \). We differentiate both sides of (3.1a) to obtain

\[
(v_n)_x(x,t) = \int_{s_n(t)}^{s_n(t)} K_n(x,\xi,t)\eta(\xi)\,d\xi + \int_0^{s_n(t)} K_n(x,\xi,t-\tau)\,d\xi + \int_0^{s_n(t)} K_n(x,\xi,t-\tau)\,d\xi + \int_0^{s_n(t)} K_n(x,\xi,t-\tau)\,d\xi.
\]

Integrating by parts in the first integral yields

\[
|((v_n)_x(x,t)| < |\eta'(x)| + (1 + W) \int_0^{s_n(t)} |K_n(x,\xi,t-\tau)|\,d\xi.
\]

Note that

\[
\int_0^{s_n(t)} |K_n(x,\xi,t-\tau)|\,d\xi = 2 \int_0^{s_n(t)} |K_n(n,t-\tau)|\,dn
\]

\[
= \int_0^{s_n(t)} e^{-(t-\tau)}\,d\tau + \frac{s_n(t)}{2(t-\tau)} e^{-n^2/4(t-\tau)}\,dn
\]

\[
= \int_0^{s_n(t)} e^{-(t-\tau)}\,d\tau + s_n(t)^{1/2} (t-\tau)^{1/2} \leq \tau_1^{1/2}.
\]

Therefore,

\[
|((v_n)_x(x,t)| < |\eta'(x)| + (1 + W)\tau_1^{1/2} \leq v_1.
\]
Differentiating both sides of (3.1b) yields
\[ |(w'_n)_n(x,t)| < \varepsilon \int_0^t |(w'_n)_n(x,n)| \, dn \]

\[ < \varepsilon \gamma_{1,T_1} \equiv W_1. // \]

**Lemma 3.3:** \((w'_n)_n(x,t)\) is a bounded continuous function in \(S_{T_1}\).

**Proof:** This follows because \(w_n' = (v_n - w_n)\) in \(S_{T_1}\). We choose \(W_2\) so that
\[ |(w'_n)_n(x,t)| < W_2 \text{ in } S_{T_1}. // \]

Let \(\bar{W} = W_1 + W_2 + W_3\).

We wish to define \(s_{n+1}(t)\) implicitly as the solution of the equation:
\[ s_{n+1}(t) = a - \theta(s_n)(t) + \Gamma(s_n)(s_n(t),t) \]
\[ s_{n+1}(0) = X_0. \]

Recall that we are assuming that \(s_n(t)\) is a smooth function in \((0,T_1)\).

\[ \bar{W} = \sup_{t \in (0,T_1)} s'(t) < \varepsilon, \text{ and given } p \in (0,T_1), \text{ there exists a constant } C_n \text{ such that} \]
\[ |s_n'(t_1) - s_n'(t_0)| < C_n |t_1 - t_0|^{1/2} \text{ for each } t_0, t_1 \in (p,T_1). \text{ From Lemmas 2.3, 2.4 and 2.5 we conclude the following.} \]

Let \(\beta(t)\) equal the right hand side of (3.4). Then,

a) \(\beta(t) \in C^1(0,T_1)\),

b) there exists constants \(K_7\) and \(K_8\) such that
\[ |\beta'(t)| < K_7 + K_8 M_n T_1^{1/2} \text{ in } (0,T_1), \]

c) there exist constants \(K_9\) and \(K_{10}\) such that
\[ |\beta'(t_1) - \beta'(t_0)| < (K_9 + K_{10} C_n T_1^{1/2}) |t_1 - t_0|^{1/2} \text{ for each } t_1, t_0 \in (p,T_1). \]

Note that the constants \(K_7\) and \(K_8\) depend only on \(\bar{W}\), and are, therefore, independent of \(n\). Furthermore, \(K_9\) and \(K_{10}\) depend on \(p\) and the bound on \(|\beta'(t)|\) given in (3.5b). Hence, \(K_9\) and \(K_{10}\) can be chosen independently of \(n\).
We conclude from Lemma 2.1 and the implicit function theorem that there exists a smooth function $s_{n+1}(t)$, defined for some time, (say $t \in [0,T_2]$), which is a solution of (3.4). We show that as long as $(s_{n+1}(t),t)$ stays in the rectangle $P$, defined in Lemma 2.1, then $s_{n+1}'(t)$ is bounded, independently of $n$.

We differentiate Equation 3.4 to obtain
\[ \psi_x(s_{n+1}'(t),t)s_{n+1}'(t) + \psi_t(s_{n+1}(t),t) = \beta(t) , \]

or
\[ (3.6) \]
\[ s_{n+1}'(t) = \frac{1}{\psi_x(s_{n+1}(t),t)} \left[ \beta(t) - \psi_t(s_{n+1}(t),t) \right] . \]

From Lemma 2.1 and (3.5b) it follows that if $(s_{n+1}(t),t) \in P$, then
\[ |s_{n+1}'(t)| < \frac{1}{\delta_2} \left[ K_7 + K_8 n^{n+1/2} + \delta_3 \right] \]
\[ = K_{11} + K_{12} n^{1/2} \]

where $K_{11} = \frac{1}{\delta_2} (K_7 + \delta_3)$ and $K_{12} = K_8 / \delta_2$ do not depend on $n$.

Suppose that $T_1 < \left( \frac{1}{2K_{12}} \right)^2$. Then, as long as $(s_{n+1}(t),t) \in P$,
\[ |s_{n+1}'(t)| < K_{11} + \frac{1}{2} H_n . \]
Hence,
\[ H_{n+1} < K_{11} + \frac{1}{2} H_n < K_{11} + \frac{1}{2} (K_{11} + \frac{1}{2} H_{n-1}) < \cdots < \]
\[ < K_{11} \left( 1 + \frac{1}{2} + \cdots + \frac{1}{2^{n-1}} \right) + 2^{-n+1} |0| < 2K_{11} + H_0 < \bar{H} . \]

Therefore, the sequence $\{s_n(t)\}$ is uniformly bounded by the constant $\bar{H}$. It follows that there exists a constant $\bar{T}$ such that $\bar{T} < T_1$, and $(s_n(t),t) \in P$ for each $t \in (0,T)$ and each $n$. Furthermore, there exists a subsequence $\{s_{n_j}(t)\}$ which converges uniformly on $[0,T]$ to a continuous function $s(t)$. We assume, without loss of generality, that $\{s_{n_j}(t)\} = \{s_n(t)\}$.
Lemma 3.4: Fix \( \rho \in (0,T) \). There exist positive constants \( K_{13} \) and \( K_{14} \) such that
\[
|s_{n+1}'(t_1) - s_{n+1}'(t_0)| < (K_{13} + K_{14} C_n T^{1/2}) |t_1 - t_0|^{1/2}
\]
for each \( n \) and \( t_0, t_1 \in (\rho, T) \). The constants \( K_{13} \) and \( K_{14} \) can be chosen independently of \( n \).

Proof: This follows from (3.5c), (3.6), and Lemma 2.1. //

We now assume that \( T < \left( \frac{1}{2K_{14}} \right)^2 \). Then the previous lemma implies that
\[
C_{n+1} < K_{13} + \frac{1}{2} C_n < \cdots < K_{13} (1 + \frac{1}{2} + \cdots + \frac{1}{2^{n-1}}) + 2^{-n} w_0
\]
\[
< 2K_{13} + C_0 = \tilde{C}.
\]
That is, given \( \rho \in (0,T) \), there exists a constant \( \tilde{C} \) such that
\[
|s_n'(t_1) - s_n'(t_0)| < \tilde{C} |t_1 - t_0|^{1/2}
\]
for each \( n \) and \( t_0, t_1 \in (\rho, T) \). It follows that \( s'(t) \) is continuously differentiable in \((0,T)\) and a subsequence of \( \{s_n'(t)\} \) converges uniformly on compact subsets of \((0,T)\) to \( s'(t) \). With loss of generality we assume that \( \{s_n'(t)\} \) converges uniformly on compact subsets of \((0,T)\) to \( s'(t) \). //

Lemma 3.5: The sequences \( \{v_n\} \) and \( \{w_n\} \) converge uniformly in \( \mathbb{R}_T \) to continuous functions \( v \) and \( w \) which satisfy the Equations (1.4).

Proof: Let \( \rho_n(t) = \sup_{x \in \mathbb{R}} \{|v_{n+1}(x,t) - v_n(x,t)| + |w_{n+1}(x,t) - w_n(x,t)|\} \). From (3.1a)
\[\text{it follows that for } (x,t) \in \mathbb{R}_T,\]
\[ |v_{n+1}(x,t) - v_n(x,t)| < \int_0^t \int_{-s_n^+(t)} s_{n+1}^+(t) K(x, \xi, t-\tau) d\xi - \]

\[ - \int_0^t \int_{-s_n^+(t)} s_n(t) K(x, \xi, t-\tau) d\xi + \int_0^t \int_{s_{n+1}^-(t)} s_{n+1}^-(t) K(x, \xi, t-\tau) d\xi - \]

\[ = \int_0^t \int_{-s_n^+(t)} s_n(t) K(x, \xi, t-\tau) d\xi + \int_0^t \int_{s_{n+1}^-(t)} s_{n+1}^+(t) K(x, \xi, t-\tau) d\xi - \]

\[ + \int_0^t \int_{-s_n^+(t)} s_n(t) K(x, \xi, t-\tau) d\xi - \]

\[ \leq 2 \sup_{0 < \tau < t} |s_{n+1}^+(t) - s_n(t)| + \int_0^t \frac{1}{2} \frac{1}{2} \sup_{x \in \mathbb{R}} |w_{n+1}(x, \tau) - w_n(x, \tau)| d\tau + \]

\[ + \int_0^t \sup_{x \in \mathbb{R}} |w_{n+1}(x, \tau) - w_n(x, \tau)| d\tau \]

\[ (3.7) \quad \leq 2T^{1/2} \sup_{0 < \tau < t} |s_{n+1}^+(t) - s_n(t)| + \int_0^t \sup_{x \in \mathbb{R}} |w_{n+1}(x, \tau) - w_n(x, \tau)| d\tau . \]

From (3.1b) it follows that for \((x, t) \in \mathcal{A}_T\),

\[ (3.8) \quad |w_{n+1}(x,t) - w_n(x,t)| < \varepsilon \int_0^t |v_{n+1}(x, \tau) - v_n(x, \tau)| d\tau . \]

Let \( \delta_n = 2T^{1/2} \sup_{0 < \tau < t} |s_{n+1}^+(t) - s_n(t)|. \) Note that \( \delta_n \to 0 \) as \( n \to \infty. \) Adding (3.7) and

\[ (3.8) \] we find that for \( t \in (0, T), \)

\[ \rho_n(t) < \delta_n + (1+\varepsilon) \int_0^t \rho_n(t) d\tau . \]
From Gronwall's inequality it follows that
\[ \rho_n(t) \leq C \delta_n \]
for some constant \( C \) independent of \( n \). Therefore \( \rho_n(t) \to 0 \) uniformly as \( n \to \infty \), and the sequences \( \{v_n\} \) and \( \{w_n\} \) converge uniformly to limit functions \( v(x,t) \) and \( w(x,t) \). Passing to the limits in (3.1) we find that \((v(x,t),w(x,t))\) satisfies the Equations (1.4). This implies that \( v \) and \( w \) are continuous functions in \( S_T \).

**Theorem 3.6:** Let \( K = \frac{1}{2} \min(\frac{1}{2}, a, a) \) and suppose that \( T < \frac{K}{2c(t)} \). Then \((v,w)\) is a classical solution of the Cauchy problem (1.1) in \( S_T \).

**Proof:** Throughout this proof we assume that \( t \in (0,T) \). Recall that \( v(x,t), w(x,t), \) and \( s(t) \) satisfy the Equations (1.4) and (1.6). Setting \( x = s(t) \) in (1.4) and subtracting the resulting equation from (1.6) we find that \( v(s(t),t) = a \).

Equation (1.4) implies that for \( |x| < s(t) \), \((v,w)\) satisfies the differential equations
\[
\begin{align*}
  v_t &= v_{xx} - v + 1 - w \\
  w_t &= s(v - vw)
\end{align*}
\]
and, for \( |x| > s(t) \), \((v,w)\) satisfies the differential equations
\[
\begin{align*}
  v_t &= v_{xx} - v - w \\
  w_t &= s(v - vw)
\end{align*}
\]
We show that \( v > a \) for \( |x| < s(t) \), and \( v < a \) for \( |x| > s(t) \). This implies that for \( x \neq s(t) \), \((v,w)\) satisfies the system of Equations (1.1).

Suppose it were not true that \( v > a \) for \( |x| < s(t) \), and \( v < a \) for \( |x| > s(t) \). For example, suppose that \( v(x_1,t_1) < a \) where \( |x_1| < s(t_1) \). Since \( v(x,0) > a \) for \( |x| < s(0) \), we may assume that \( v(x_1,t_1) = a \) and \( v(x,t) > a \) in the region...
G = \{(x,t) : |x| < s(t), t \in (0,t_1)\}. We use the maximum principle (see [6], page 159) to show that this is impossible. Note that \( v = a \) for \(|x| = s(t)\) and \( v(x,0) > a \) for \(|x| < x_0\). Let \( L \) be the operator defined by \( Lw = v_t - v_{xx} + v \). Then, in \( G \), \( Lw = 1 - w \). From (1.4b) it follows that in \( \mathbb{R} \times (0,t_1) \),

\[
|w(x,t)| < \varepsilon \int_0^T |v(x,n)| \, dn
\]

(3.11)

\[< \varepsilon VT < K.\]

Therefore, in \( G \), \( Lw > 1 - K > a = L(a) \). It now follows from the maximum principle that \( v(x_1,t_1) > a \). This is a contradiction. A similar argument shows that it is impossible for \( v > a \) for \(|x| > s(t)\).

We have shown that except for \( x \neq s(t) \), \((v,w)\) satisfies the system of equations (1.1) in \( S_0 \). It remains to show that \( v(x,T) \) exists for \(|x| = s(t)\).

Assume that \(|x| < s(t)\) and \(|\xi| < s(T)\). Then \((v(\xi,T),w(\xi,T))\) satisfies the system of equations

\[
\begin{align*}
v_t - v_{\xi\xi} + v &= 1 - w \\
w_t &= v - \gamma w.
\end{align*}
\]

Multiply both sides of the first equation by \( K(x-\xi,t-T) \), integrate by parts, and use the fact that \( K_{\xi} + K_{\xi\xi} - K = 0 \) to obtain:

\[
(Kv)_\tau - (Kv_\xi)_{\xi} + (Kw)_{\xi\xi} = (1 - w)K .
\]

We integrate this last equation for \(-s(T) < \xi < s(T)\), \( \delta < T < T - \delta \), and let \( \delta \to 0 \) to obtain:
\[ v(x,t) = -\int_{x_0}^{x} K(x-s(\tau),t-\tau) s'(\tau) d\tau \]

\[ -\int_{0}^{t} K(x+s(\tau),t-\tau) s'(\tau) d\tau - \int_{0}^{t} K(x-s(\tau),t-\tau) v(\xi) (s(\tau),\tau) d\tau \]

(3.12a)

\[ + \int_{0}^{t} K(x+s(\tau),t-\tau) v(\xi) (-s(\tau),\tau) d\tau + \int_{0}^{t} a K(\xi) (x-s(\tau),t-\tau) d\tau \]

\[ - \int_{0}^{t} a K(\xi)(x+s(\tau),t-\tau) d\tau \]

\[ = \int_{0}^{t} d\tau \int_{s(\tau)}^{\xi} (1-w) K(x-\xi,t-\tau) d\xi \]

Next assume that \( \xi > s(\tau) \). Then \( v(\xi,t) \) satisfies the differential equation

\[ v_{\tau} - v_{\xi \xi} + v = -w \]

Multiply both sides of this equation by \( K(x-\xi,t-\tau) \) and integrate by parts to obtain:

\[ (Kv)_{\xi} = (Kv)_{\xi} + (Kv)_{\xi} = -Kv \]

Integrate this last equation for \( s(\tau) < \xi < \cdot \), \( \delta < \tau < t - \delta \) and let \( \delta \to 0 \) to obtain:

\[ -\int_{0}^{t} K(x-\xi,t) v(\xi) d\xi + \int_{0}^{t} K(x-s(\tau),t-\tau) s'(\tau) d\tau \]

(3.12b)

\[ + \int_{0}^{t} K(x-s(\tau),t-\tau) v(\xi) (s(\tau),\tau) d\tau - \int_{0}^{t} a K(\xi) (x-s(\tau),t-\tau) d\tau \]

\[ = \int_{0}^{t} d\tau \int_{s(\tau)}^{\xi} K(x-\xi,t-\tau) w(\xi,\tau) d\xi \]

Similarly, for \( \xi < s(\tau) \) we obtain:

\[ \int_{0}^{t} K(x-\xi,t-\tau) d\xi + \int_{0}^{t} K(x+s(\tau),t-\tau) s'(\tau) d\tau \]

(3.12c)

\[ - \int_{0}^{t} K(x+s(\tau),t-\tau) v(\xi) (-s(\tau),\tau) d\tau \]

\[ + \int_{0}^{t} a K(\xi)(x+s(\tau),t-\tau) d\tau = \int_{0}^{t} d\tau \int_{s(\tau)}^{\xi} K(x-\xi,t-\tau) w(\xi,\tau) d\xi \]
Adding (3.12a), (3.12b), and (3.12c), and using (1.6) we find that

\[
(3.13) \quad \int_0^\infty [K(x-s(t),t-t)[\varphi'(s(t)^+,t) - \varphi'(s(t)^-,t)]
+ K(x+s(t),t-t)[\varphi'(s(t)^-,t) - \varphi'(s(t)^+,t)]] \, dt = 0.
\]

Using the assumption that \( \varphi(x) = \varphi(-x) \) it follows from (1.4) that \( \varphi(x,t) = \varphi(-x,t) \) in \( S_r \). Therefore, (3.13) can be rewritten as

\[
\int_0^\infty [K(x-s(t),t-t) - K(x+s(t),t-t)][\varphi'(s(t)^+,t) - \varphi'(s(t)^-,t)] \, dt = 0.
\]

Since \( K(x-s(t),t-t) - K(x+s(t),t-t) > 0 \) in \( (0,T) \) we conclude that \( \varphi'(s(t)^-,t) = \varphi'(s(t)^+,t) \) in \( (0,T) \).

We have shown that \( \varphi'(x,t) \) is a bounded continuous function in \( S_r \). From (1.4b) it follows that \( \varphi''(x,t) \) is also a bounded continuous function in \( S_r \). //
REFERENCES


The pure initial value problem for the system of equations

\[ v_t = v_{xx} + f(v) - w \]

\[ w_t = \varepsilon(v - \gamma w) \]

is considered. Here \( \varepsilon \) and \( \gamma \) are positive constants, and
f(v) = v - H(v - a) where H is the Heaviside step function and 
\( a \in (0, \frac{1}{2}) \). Because of the discontinuity in \( f \) one cannot expect the 
solution of this system to be very smooth. Sufficient conditions on the 
initial data are given which guarantee the existence of a classical solution 
in \( \mathbb{R} \times (0, T) \) for some positive time \( T \).