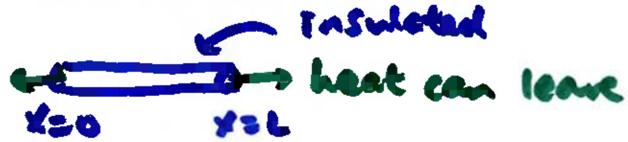
9.5 Heat Equation (part 2)

$u_t = k u_{xx}$



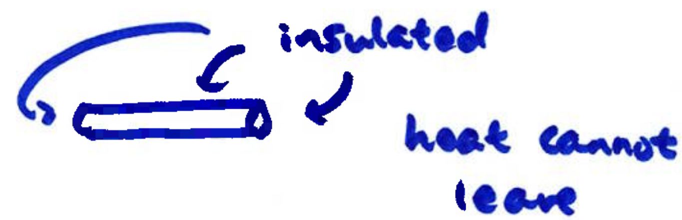
$u(0,t) = u(L,t) = 0$

$u(x,0) = f(x)$

Solution: $u(x,t) = \sum_{n=1}^{\infty} b_n e^{-kn^2\pi^2 t/L^2} \sin\left(\frac{n\pi x}{L}\right)$

$$b_n = \frac{2}{L}\int_0^L f(x)\sin\left(\frac{n\pi x}{L}\right)$$

now we look at the insulated version



$u_t = k u_{xx}$

BC's: $u_x(0,t) = u_x(L,t) = 0$ → rate $= 0$ → heat cannot travel out the rod

IC: $u(x,0) = f(x)$

apply method of separation again: $u(x,t) = X(x)T(t)$

$X'(0) = X'(L) = 0$

Same eigenvalues : $\lambda_n = \frac{n^2\pi^2}{L^2}$

eigenfunctions: $X_n = \cos\left(\frac{n\pi x}{L}\right)$

Same T_n: $T_n = e^{-kn^2\pi^2 t/L^2}$

Solutions: $u_n = e^{-kn^2\pi^2 t/L^2}\cos\left(\frac{n\pi x}{L}\right)$ $\quad n = 0, 1, 2, 3, \ldots$

$u_0 = 1$

general solution:

$$\boxed{u(x,t) = \frac{1}{2}a_0 u_0 + \sum_{n=1}^{\infty} a_n e^{-kn^2\pi^2 t/L^2}\cos\left(\frac{n\pi x}{L}\right)}$$

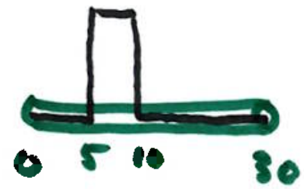
$u(x,0) = f(x)$

$f(x) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} a_n \cos\left(\frac{n\pi x}{L}\right)$ cosine series

$$\boxed{a_n = \frac{2}{L}\int_0^L f(x)\cos\left(\frac{n\pi x}{L}\right)dx}$$

example Insulated ends

$L = 30,\quad K = 1 \qquad f(x) = \begin{cases} 0 & 0 < x < 5 \\ 25 & 5 < x < 10 \\ 0 & 10 < x < 30 \end{cases}$



physical intuition: temperature evens out as $t \to \infty$

temp expected to be $\frac{(5)(25)}{30} = \text{avg.} = \frac{25}{6}$

put $L = 30$, $K = 1$, $f(x)$ into solution on last page

$a_0 = \cdots = \frac{25}{3} \qquad a_n = \cdots = \frac{50}{n\pi}\left[\sin\left(\frac{n\pi}{3}\right) - \sin\left(\frac{n\pi}{6}\right)\right]$

first few terms:

$$u(x,t) = \frac{25}{6} + 3.5\, e^{-\pi^2 t/900} \cos\left(\frac{n\pi x}{30}\right) + -3.2\, \underbrace{e^{-9\pi^2 t/900}}_{\text{large exponent}} \cos\left(\frac{3\pi x}{30}\right)$$

$$- 4.1\, \underbrace{e^{-16\pi^2 t/900}}_{\text{large exponent}} \cos\left(\frac{4\pi x}{30}\right) + \cdots$$

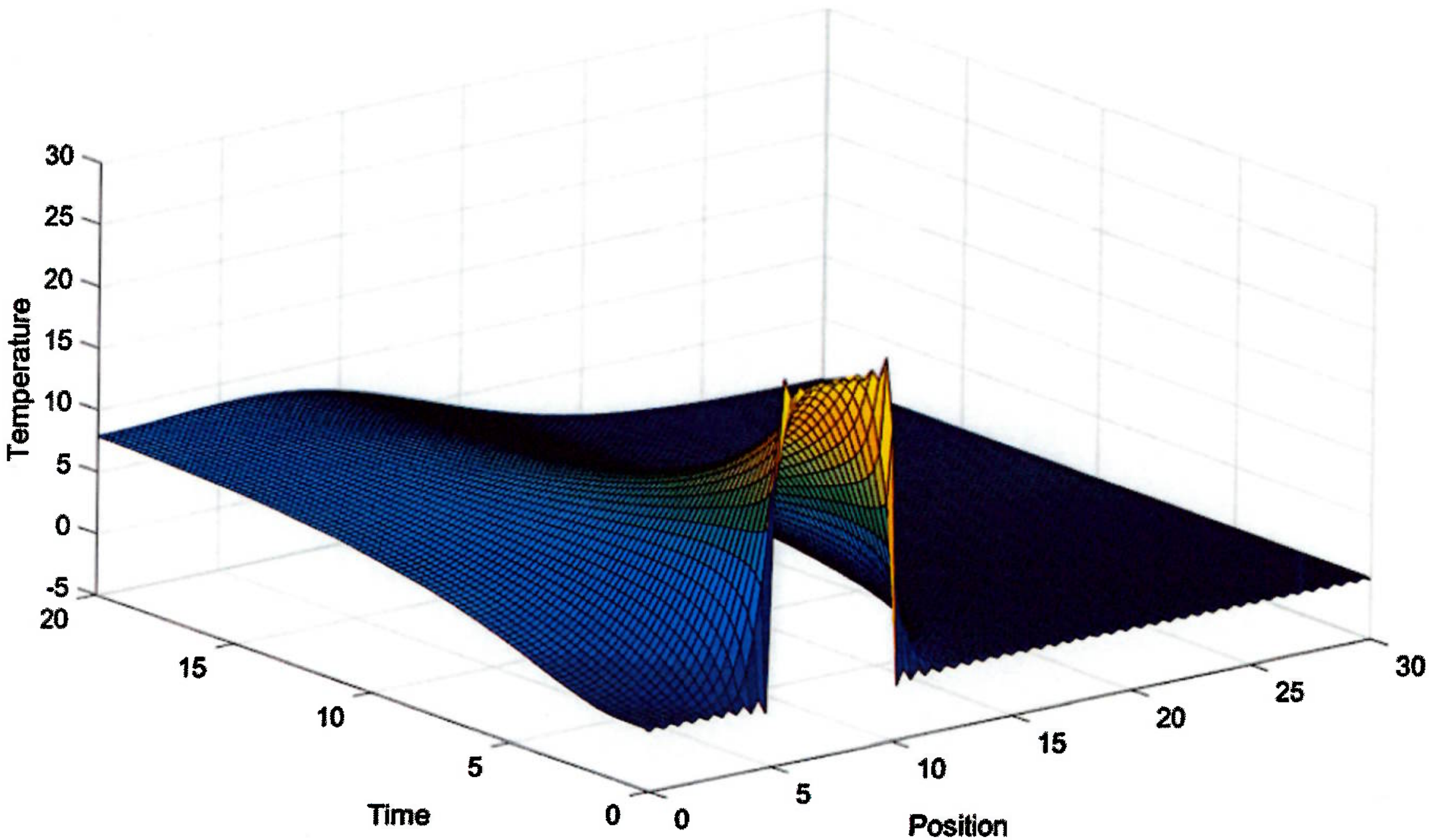
negative exponential $\to$ fast convergence

as $t \to \infty \qquad u \to \frac{25}{6}$

temp $= \frac{25}{6}$

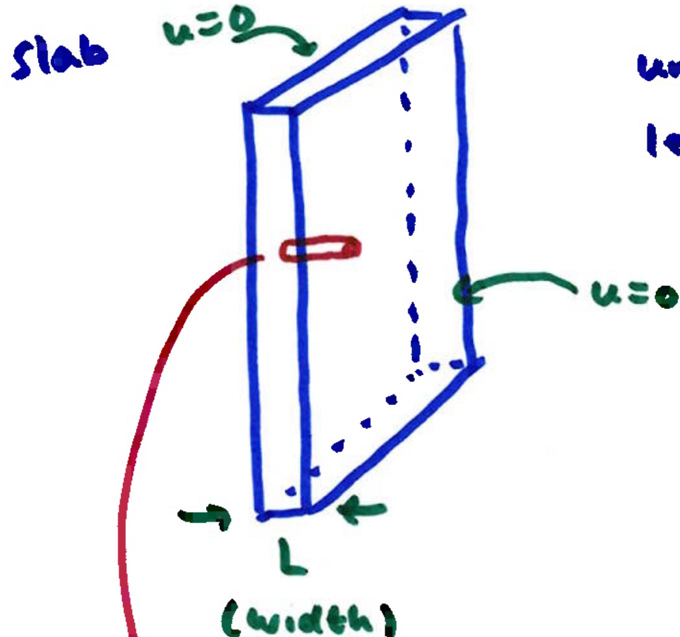
steady-state solution

transient solution : before $t \to \infty$


Temperature
30
25
20
15
10
5
0
-5
20
15
10
5
0
Time
0
5
10
15
20
25
30
Position

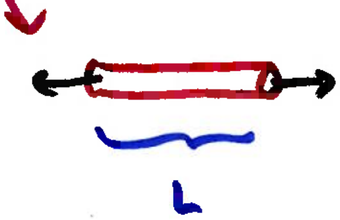
back to the non-insulated solution

this can be applied to something like this:



uniformly heated

left and right faces are kept at 0 at all t



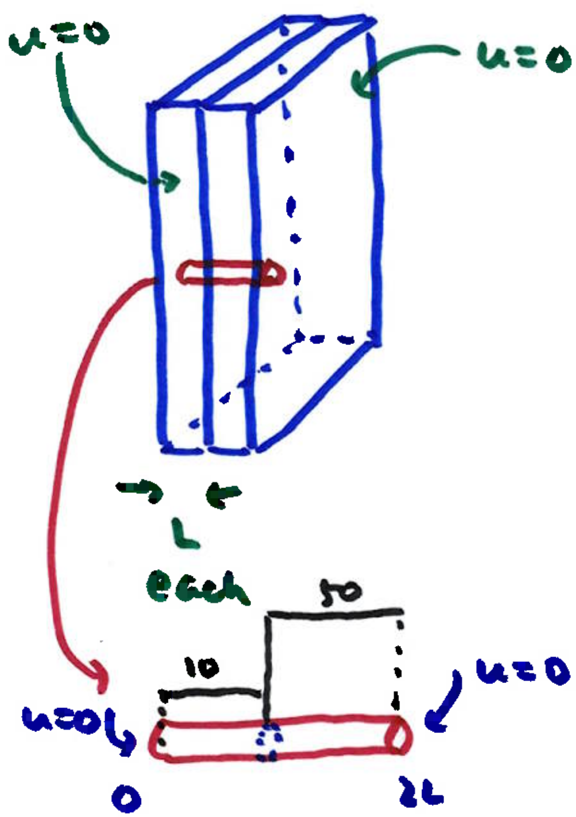
uniformly heated → no temp gradient laterally

no lateral heat flow

→ as if laterally insulated

↑

solve w/ basic heat equation solution we derived two such slabs ~~stake~~ stacked together



uniformly heated (each slab)

two outer faces held at temp = 0

each slab at potentially different temps

for example, left slab at 10

right slab at 50

→ same as rod length 2L

$$u(0,t) = u(2L,t) = 0$$

$$f(x) = \begin{cases} 10 & 0<x<L \\ 50 & L<x<2L \end{cases}$$

can reuse solution derived

if not uniformly heated → 2D or 3D heat equation

$$u_t = k(u_{xx} + u_{yy})$$

<u>example</u> : slab 4 cm thick made of copper ($k = 1.15\ cm^2/s$)

Both faces kept at 0°c

Initially entire interior heated to 100°c

Find temp at center 3 seconds later

How long before center cools to 5°c ?

$$u(x,t) = \sum_{n=1}^{\infty} b_n e^{-kn^2\pi^2 t/L^2} \sin\left(\frac{n\pi x}{L}\right)$$

$$b_n = \frac{2}{L}\int_0^L f(x)\sin\left(\frac{n\pi x}{L}\right)dx$$

$L = 4$ $\quad f(x) = u(x,0) = 100$ $\quad u(0,t) = u(4,t) = 0$

plug in, find b_n

$$u(x,t) = \sum_{n=1}^{\infty} \frac{200}{n\pi}\left[1-(-1)^n\right] e^{-1.15n^2\pi^2 t/16} \sin\left(\frac{n\pi x}{16}\right)$$

negative exponential fast conv.

3 terms enough (3 non-zero)

center temp 3 sec later

$$u(2,3) \approx 15.16°c$$

How long before center cools to $5°c$?

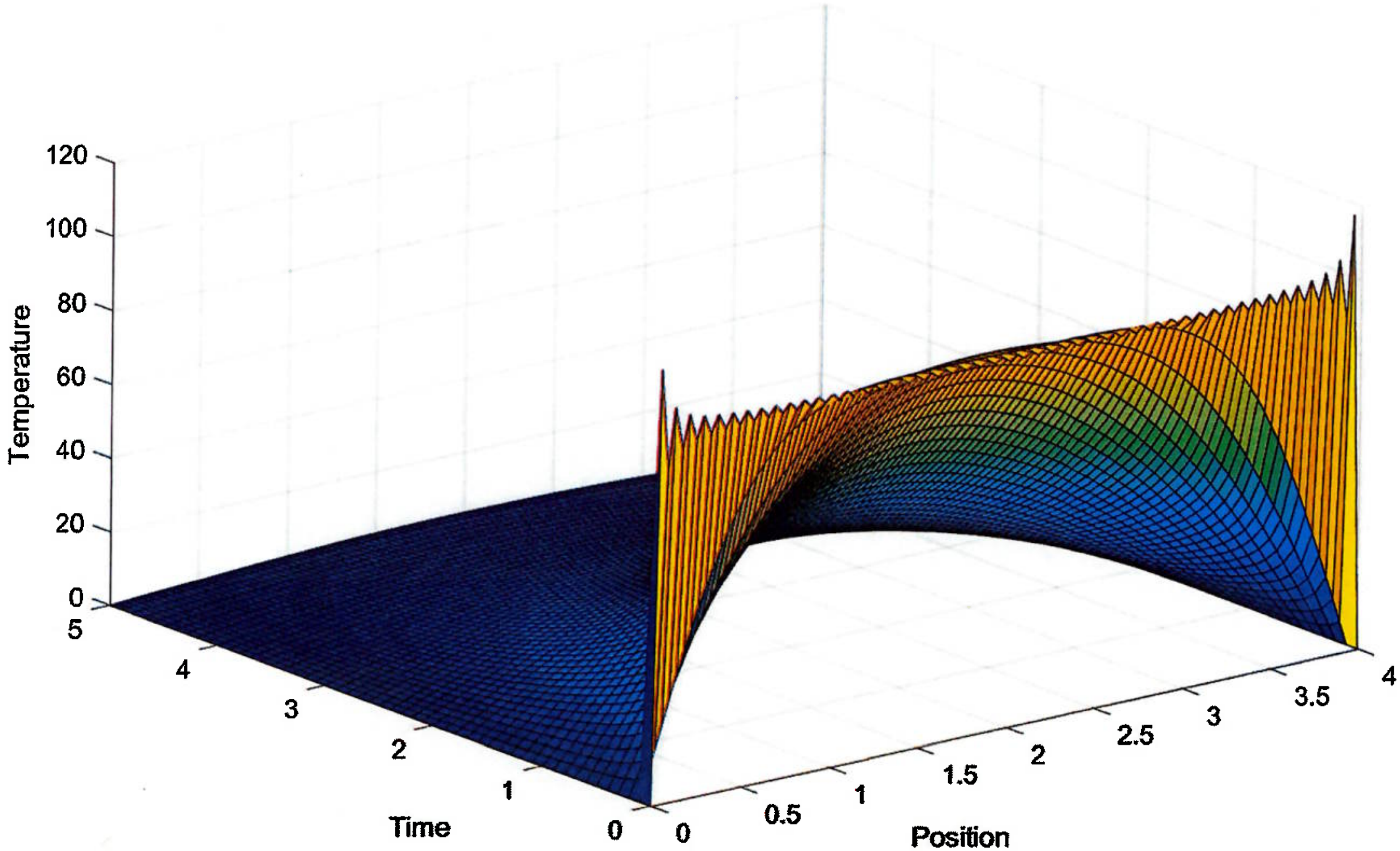
even longer time, fast converging series $\rightarrow$ 1 non-zero term

$$u(x,t) = \frac{400}{\pi} e^{-1.15\pi^2 t/16} \sin\left(\frac{\pi x}{4}\right)$$

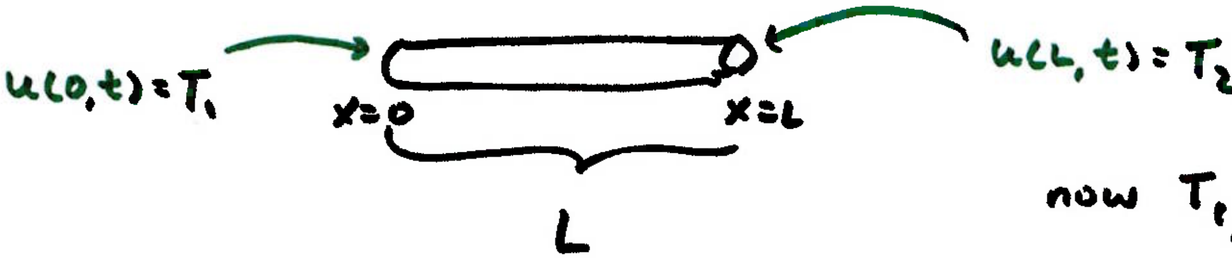
Center: $x = 2$

$$u(2,t) = \frac{400}{\pi} e^{-1.15\pi t^2/16} \underbrace{\sin\left(\frac{\pi}{2}\right)}_{1} = 5$$

Solve for t: $t \approx 4.6$ seconds


Temperature
120
100
80
60
40
20
0
5
4
3
2
1
0
Time
0
0.5
1
1.5
2
2.5
3
3.5
4
Position

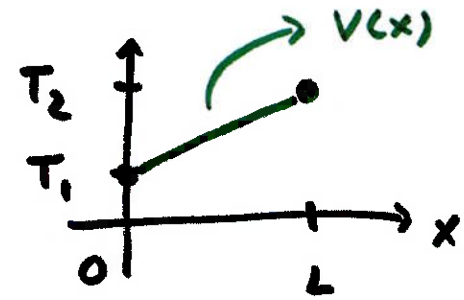
now we will let the boundary conditions be nonhomogeneous



now T_1, T_2 can be nonzero

$$u_t = k u_{xx}$$

let $V(x) = T_1 + \frac{T_2 - T_1}{L} x$



let $w(x,t) = u(x,t) - V(x)$

note $\boxed{\begin{aligned} w(0,t) &= u(0,t) - V(0) = 0 \\ w(L,t) &= u(L,t) - V(L) = 0 \end{aligned}}$

note $w(x,t)$ has homogeneous BC's

$$u_t = \frac{\partial}{\partial t}\left(u\right) = \frac{\partial}{\partial t}\left(w + V\right) = w_t + 0 \longleftrightarrow u_t = w_t$$

$$u_{xx} = \frac{\partial}{\partial x}\left(\frac{\partial}{\partial x}\left(u\right)\right) = \frac{\partial}{\partial x}\left(\frac{\partial}{\partial x}\left(w + V\right)\right) = \frac{\partial}{\partial x}\left(w_x + \frac{T_2 - T_1}{L}\right)$$

$= w_{xx} + 0 \rightarrow u_{xx} = w_{xx}$

so, $u_t = k u_{xx} \Longrightarrow$ $\boxed{\begin{aligned} &w_t = k w_{xx} \\ &w(0,t) = 0 \\ &w(L,t) = 0 \\ &w(x,0) = u(x,0) - v(x) \\ &\qquad\quad = f(x) - v(x) \end{aligned}}$

same as before, except the final BC

solution: $w(x,t) = \sum_{n=1}^{\infty} b_n e^{-kn^2\pi^2 t/L^2} \sin\left(\frac{n\pi x}{L}\right)$

or, since $u(x,t) = v(x) + w(x,t)$

$$u(x,t) = v(x) + \sum_{n=1}^{\infty} b_n e^{-kn^2\pi^2 t/L^2} \sin\left(\frac{n\pi x}{L}\right)$$

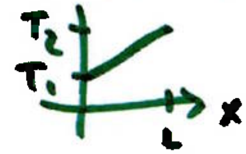
$$\boxed{u(x,t) = \left(T_1 + \frac{T_2 - T_1}{L} x\right) + \sum_{n=1}^{\infty} b_n e^{-kn^2\pi^2 t/L^2} \sin\left(\frac{n\pi x}{L}\right)}$$

at $t=0$, $u(x,0) = f(x)$

$$\left[f(x) - \left(T_1 + \frac{T_2 - T_1}{L} x\right)\right] = \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi x}{L}\right)$$

$$\boxed{b_n = \frac{2}{L}\int_0^L \left[f(x) - \left(T_1 + \frac{T_2 - T_1}{L}x\right)\right] \sin\left(\frac{n\pi x}{L}\right) dx}$$

solution as $t \to \infty$ $\quad u(x,t) \to \left(T_1 + \frac{T_2 - T_1}{L}x\right)$ steady-state solution is



steady state solution could have been found from heat eq. easily

$u_t = k u_{xx}$ when time doesn't matter any more $\to u_t = 0$

$$k u_{xx} = 0$$

$$u_{xx} = 0$$

$$u_x = C_1$$

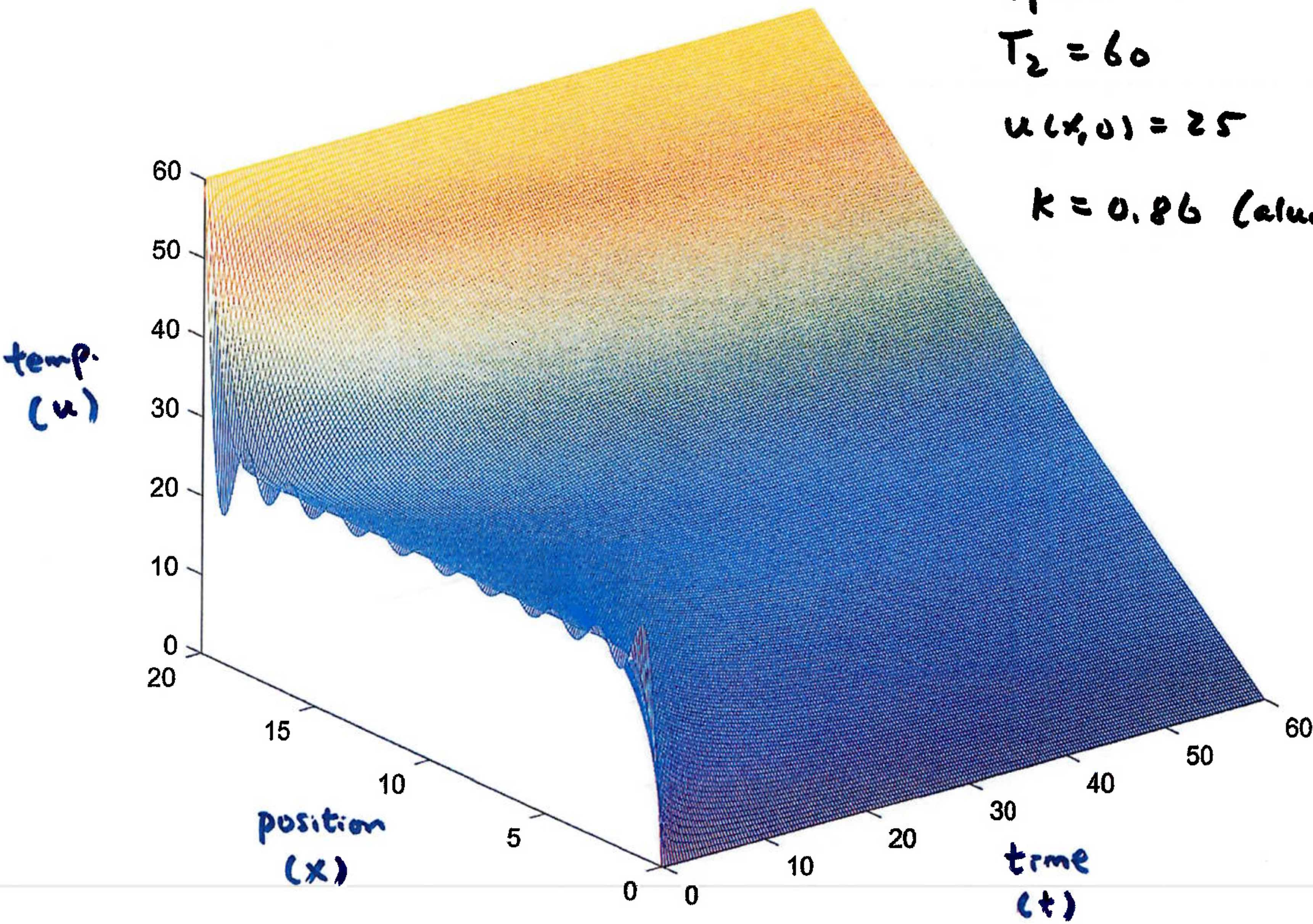
$u = C_1 x + C_2 \to$ same as $\left(T_1 + \frac{T_2 - T_1}{L}x\right)$

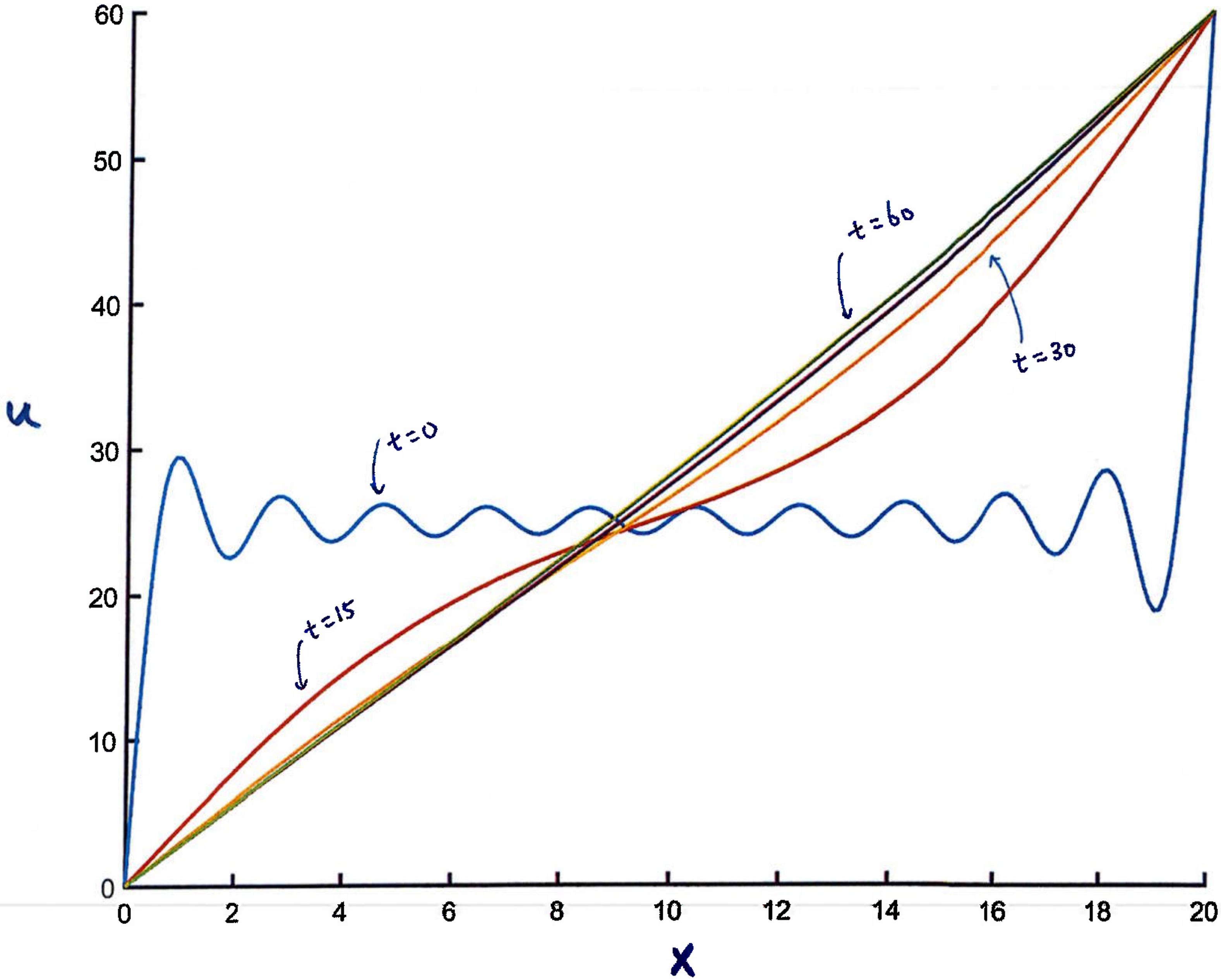
$T_1 = 0$

$T_2 = 60$

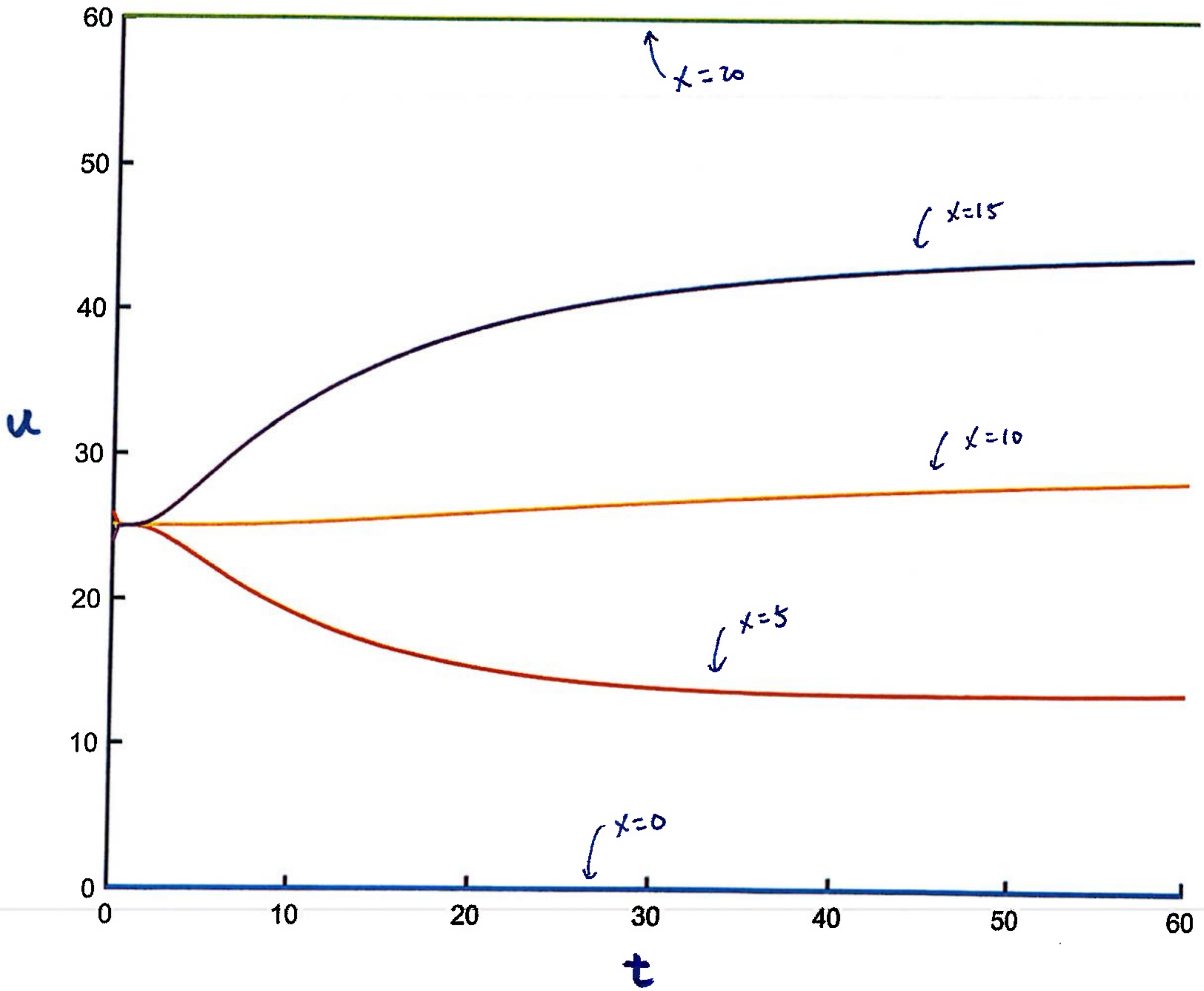
$u(x,0) = 25$

$k = 0.86$ (aluminum)





60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
u
X
t=0
t=15
t=30
t=60



60
50
40
30
20
10
0
u
x=20
x=15
x=10
x=5
x=0
0
10
20
30
40
50
60
t